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LEVEL II

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AFATL-TR-77-58

GAU-8

30mm Gun Barrel Rifling Development

AD B028651

AERONUTRONIC FORD CORPORATION
AERONUTRONIC DIVISION
FORD ROAD
NEWPORT BEACH, CA. 92663

APRIL 1977

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FINAL REPORT FOR PERIOD JUNE 1976-MARCH 1977

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFATL-TR-77-58	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): GAU-8 GUN BARREL RIFLING DEVELOPMENT.	5. TYPE OF REPORT & PERIOD COVERED: Final June 1976 — March 1977
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Richard A. Harlow, Donald P. Haas	8. CONTRACT OR GRANT NUMBER(s): F08635-76-C-0284
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Aeronutronic Division, Aeronutronic Ford Corporation, Ford Road, Newport Beach, California 92663	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: PE 63601F, JON 670F-01-38
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Armament Laboratory, Armament Development and Test Center, Eglin Air Force Base, Florida 32542	12. REPORT DATE: April 1977
	13. NUMBER OF PAGES: 54
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in DDC

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

30mm Gun Barrels
Gain Twist Rifling
Plastic Rotating Bands
Finite Element Computer Analysis
Sawtooth Rifling
Modified Conventional Rifling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A 9-month program was conducted to develop improved 30mm GAU-8 rifling and deliver test barrels to the Air Force which incorporated the new rifling designs. Gain twist rifling was designed. Two rifling groove configurations, modified conventional and sawtooth, were designed based on thermal analysis, rotating band engraving considerations and FINE code analysis. Two 30mm GAU-8 barrels with modified conventional gain twist rifling and two barrels with sawtooth gain twist rifling were fabricated and delivered to the Air Force.

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SUMMARY

The objective of the program was to design improved 30mm GAU-8 rifling and to fabricate test barrels incorporating the new rifling design for delivery to the Air Force.

A detailed analysis of rifling twist was performed, and a gain twist design was selected over the presently used constant twist to minimize stresses on the projectile rotating band.

Two basic types of rifling groove configurations were also analyzed, i.e., modified conventional and sawtooth. Thermal analyses, band engraving analyses, and FINE code analyses were employed to optimize the number of lands and grooves as well as groove shape. Both configurations were finally selected to include 24 lands and grooves. The designs selected are shown in Figure 5 of this report.

Four GAU-8 barrels were fabricated utilizing production barrel blanks and processing techniques except for the specified rifling. Gain twist rifling was utilized and two barrels were fabricated with modified conventional and two with sawtooth configurations. No difficulty was experienced in utilizing the rifling tooling developed for the two configurations. The barrels were finish machined, proof fired, and delivered to the Air Force.

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PREFACE

This report was prepared by Aeronutronic Ford Corporation, Aeronutronic Division, Newport Beach, California, under Contract No. F08635-76-C-0284 with the Air Force Armament Laboratory, Eglin Air Force Base, Florida. The report covers work performed from June 1976 to March 1977. Mr. David G. Uhrig (DLDG) was the program manager for the Armament Laboratory.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

GERALD P. D'ARCY, Colonel, USAF
Chief, Guns, Rockets and Explosives Division

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INTRODUCTION

The use of plastic rotating bands on medium caliber projectiles shows a significant potential for reducing barrel erosion and improving ballistic performance. Although considerable effort has been expended on plastic band development, performance difficulties, primarily involving band integrity still exist.

As demonstrated in the Optimum Rifling Configuration for Plastic Rotating Bands Programs, Contracts F08635-75-C-0041 and F08635-76-C-0204, rifling twist configuration and rifling land profiles can be modified to reduce peak torque levels and improve distribution of torque induced stresses within the band material and at the driving interface with the projectile. Gain twist type rifling can reduce peak torques by approximately 50 percent and can be profiled to minimize torque at the entrance cone, thus improving band survivability during the engraving process, particularly with worn or hot barrels.

Additional improvements have been demonstrated with sawtooth and modified conventional rifling profiles in 20mm barrels. These improvements include generally lower failure rates of highly stressed driving bands under constant test conditions. In addition, sawtooth rifling offers the capability of firing bands of significantly greater diameter than could be fired in a conventionally rifled barrel which provides better obturation and more uniform ballistic performance under worn and hot barrel conditions. The combination of gain twist and sawtooth or modified conventional rifling profiles for the GAU-8 weapon will potentially eliminate or significantly reduce rotating band failures.

In June 1976 the Air Force awarded Contract F08635-76-C-0284 with the objective of developing improved rifling for 30mm GAU-8 gun barrels. The GAU-8 gun system currently uses gun barrels which have constant twist rifling, and fires projectiles with plastic rotating bands. Some problems have been encountered with projectile instabilities, possibly attributable to the rifling design. This program involved designing improved rifling and fabricating test barrels incorporating two new rifling designs for delivery to the Air Force.

This final report documents the work performed on this contract. Sections II and III present details of the design and analysis work and discuss barrel fabrication. Conclusions and recommendations are presented in Section IV.

SECTION II

DESIGN AND ANALYSIS

2.1 BACKGROUND DATA

Input design and interior ballistics data supplied by the Air Force to be used in this analysis included:

- G.E. Drawings: 201F158 Barrel, 30mm
  and
  201F400 Cartridge - Gun Interface, 30mm

- A representative internal ballistics computer run (Appendix I)

- Limited descriptive information concerning the overall configuration of the two candidate plastic bands (Figures 1 and 2)

A review of existing chamber dimensions and plating specifications was made to evaluate the design freedom available for modification of the rifling. It was concluded that the maximum groove diameter that could be obtained without grooving the chamber in the vicinity of the band relief was 1.238 inches if the current plating specifications for chamber and bore were to be retained. Somewhat larger groove diameters were included in the parametric studies, however, to determine if a significant influence of bore diameter on band performance might warrent revision of the chamber design or plating specifications

The statement of work required the development of two rifling designs, one based upon the sawtooth rifling profile, and the second configuration based upon the modified conventional profile, which were developed and tested in 20mm caliber under Contracts F08635-75-C-0041 and F08635-76-C-0204. The modified conventional profile differs from conventional rifling primarily by larger root fillets, more lands and narrower land width. Both rifling designs were to incorporate a gain twist.

2.2 RIFLING TWIST ANALYSIS

A program was written to evaluate torque/distance profiles for constant twist, gain twist, and increasing gain twist rifling. The computations were made for gain twist profiles following short zero twist entrance sections of 0 to 4.8 inches. This zero twist section is included to reduce the initial torque impact in event of entrance cone erosion. Based upon comments from Eglin AFB, the erosion obtained using plastic driving bands is very small so inclusion of the zero twist section may be quite conservative. A 3-inch zero twist

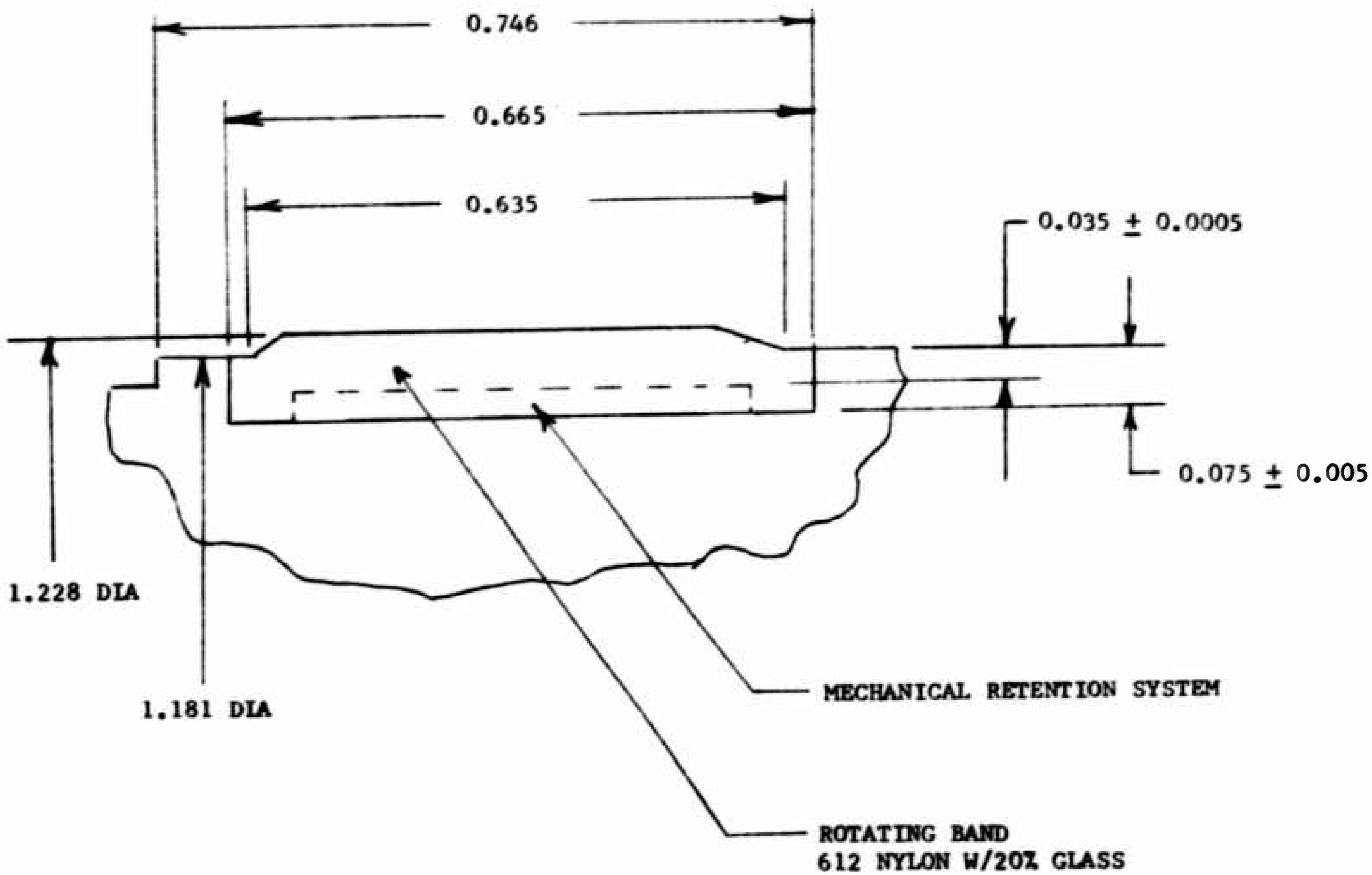


Figure 1. Plastic Band Candidate I

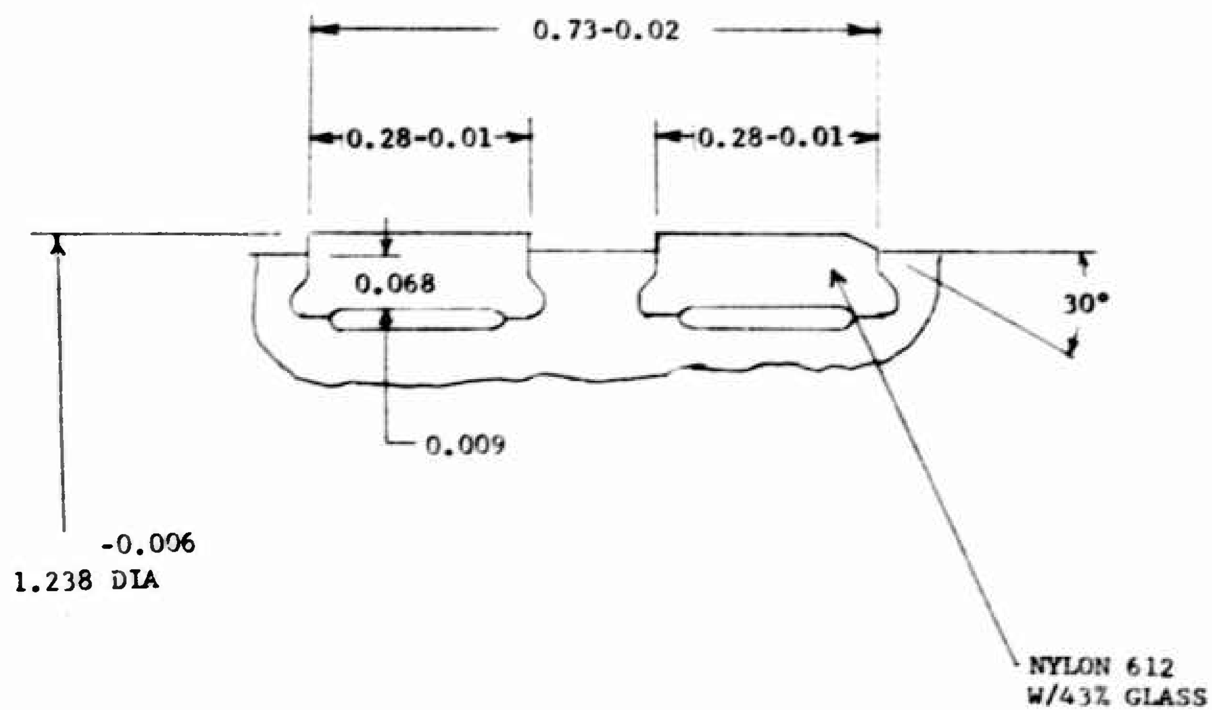


Figure 2. Plastic Band Candidate II

section was included at small penalty to peak torque required (approximately 3 percent). Also, a constant twist exit section at the muzzle was included to minimize projectile tip-off in event of muzzle end rifling damage or partial driving band failure. Muzzle exit torque is reduced by a factor of 4 from that obtained with retaining gain, twist to the exit.

Prior analyses have been concerned with the wiping action of gain twist rifling configurations on the engraved band. A 9.9-degree gain twist has the effect of wiping 0.120 inch in a band length of 0.7 inch. This is equivalent to a 12.5-degree shear of one end of the driving band. The interior ballistics data used for the final rifling study are contained in Table 1. Projectile dimensional and mass properties data were supplied by Eglin AFB and are summarized in Table 2.

The torque histories are computed using:

$$\tau_x = \frac{M}{r} k^2 \left(u_x^2 \, \frac{d \tan \theta_x}{dx} + \tan \theta_x \, \frac{p_x \pi r^2}{M} \right)$$

where

M	is projectile mass
k	is the radius of gyration
r	is projectile radius
u_x	is instantaneous velocity of projectile
θ_x	is twist angle at station x
x	is distance from projectile rest position
p_x	is barrel pressure at projectile

This assumes a rigid driving band. For the case of exponential gain twist rifling following a straight entrance section this equation predicts infinite torque at the transition to gain twist for exponents less than 2.0. This is primarily a mathematical problem in that the actual displacements (y) are infinitesimal and with a compliant driving band these torques cannot be developed in real life. Referring to Figure 3, the minimum in the predicted torque curve for the gain twist profile occurs at x = 3.6 inches. The y displacement at this station is only 0.003 inch. At x stations between 3.0 and 3.2 inches where the computed torque exceeds 1200 in-lb, the displacements are less than 0.0005 inch. Alternate transition sections that would theoretically limit the entrance torque have also been explored. The approach was to select a twist curvature based upon a constant d^2y/dx^2 and blend into the exponential gain twist profile. Figure 3 indicates the torque profile that can be developed using this technique. The transition section would extend over 1.6 inches

TABLE 1. 30MM INTERIOR BALLISTICS DATA

Time (Sec)	Projectile Base Pressure (Psi)	Projectile Velocity (Fps)	Travel (In.)
0.00120	52978.7	766.13	2.235
0.00125	53940.8	866.93	2.724
0.00130	54076.9	968.37	3.275
0.00135	53498.9	1069.03	3.886
0.00140	52348.0	1167.77	4.557
0.00150	48909.5	1356.31	6.073
0.00160	44767.2	1530.01	7.806
0.00170	40578.8	1687.88	9.739
0.00180	36682.2	1830.62	11.851
0.00190	33181.5	1959.61	14.126
0.00200	30090.7	2076.40	16.549
0.00210	27396.0	2182.48	19.105
0.00230	22984.4	2376.87	24.572
0.00250	19571.7	2524.40	30.448
0.00270	16912.2	2658.52	36.671
0.00290	13857.7	2771.73	43.192
0.00310	11374.0	2863.44	49.958
0.00330	9536.6	2939.32	56.924
0.00370	7048.3	3058.08	71.333
0.00405	5640.9	3137.40	84.350

TABLE 2. PROJECTILE CHARACTERISTICS

Weight	5600 Grains
Axial Inertia	0.1542 lb/in^2
Base Diameter	1.184 in.

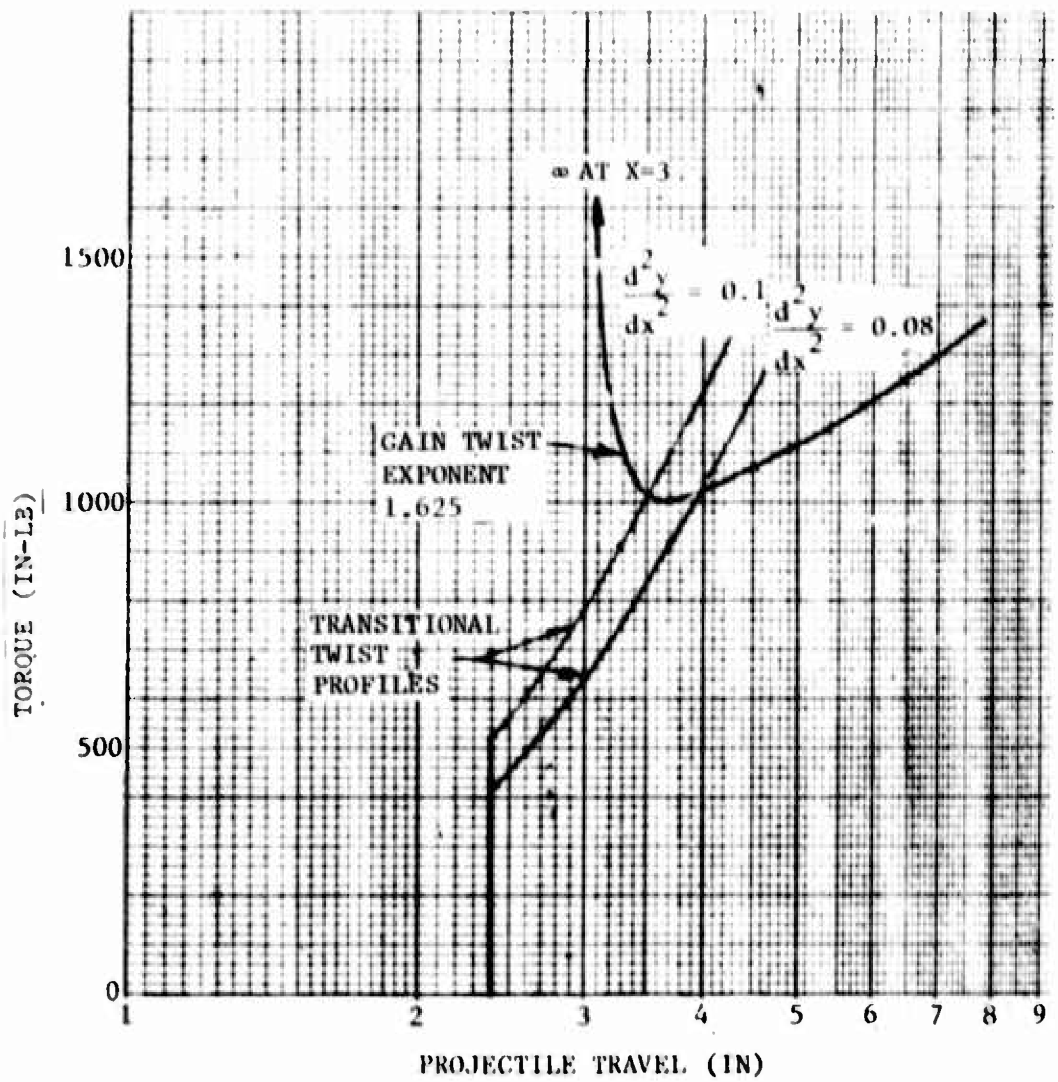


Figure 3. Use of Transitional Profile to Limit Transitional Torque-Rigid Band Assumption

of travel and blends into the gain twist profile at a y displacement of 0.005 inch. This transition is not implemented in the selected profile, however.

Figure 4 defines the torque/travel characteristics for constant twist and exponential gain twist profiles varying the exponent from 1.55 to 1.625. In all cases the exit twist angle is 9.9 degrees (equivalent to the current GAU-8 design). The effect of varying the gain twist exponent is seen to be the shift of torque impulse from the first third of projectile travel into the remaining two-thirds. An exponent of 1.625 is typically used in gain twist rifling as a reasonable compromise of initial torque level in the breech region where thermal growth and wear are greatest and final torque where band wear and deformation due to rifling angle change are greatest. Based upon the results of Figure 4 there is no substantial reason to change from a 1.625 exponent.

The effect of increasing the length of zero twist section at barrel entrance was also explored briefly. For a 4.8-inch zero twist length versus 3 inches the increase in torque in the first several inches of gain twist section was about 6 percent reducing to a 2 percent penalty at the muzzle. Typical practice is to use 0 to 3 calibers of zero twist prior to the gain twist section. The selected 3-inch section is approximately 2.5 calibers. The selected twist configuration is summarized in Figures 5 and 6.

2.3 RIFLING PROFILE ANALYSIS

2.3.1 THERMAL ANALYSIS

The limited thermal analysis was directed at establishing that the modified rifling configurations would not result in more severe land surface temperatures under rapid fire conditions than the existing GAU-8 rifling configuration. Also, an evaluation of barrel surface and bulk temperature at three barrel stations was made to evaluate if there was a substantial barrel thermal growth gradient towards the muzzle end which could affect obturation of plastic bands under hot barrel conditions.

The land surface temperature comparison was performed using a two dimensional model of radial segments of the barrel evaluated at a station 1.5 inches beyond the start of rifling. Three section profiles were modeled, the current 20 land GAU-8 configuration excluding root fillets and two sawtooth configurations with land widths of 0.049 and 0.040 inch and an 0.020 root fillet radius. It was concluded that the modified configurations also provided adequate modeling of the modified conventional rifling for thermal evaluation and conclusions are, therefore, also drawn concerning the selected modified conventional configuration.

The lumped parameter nodal matrices used in the analysis of two of the cases are shown in Figures 7 and 8. These cases are the 20 land and groove conventional and sawtooth rifling shapes and are modeled as radial segments of barrel. One-half of the conventional land/groove configuration is modeled

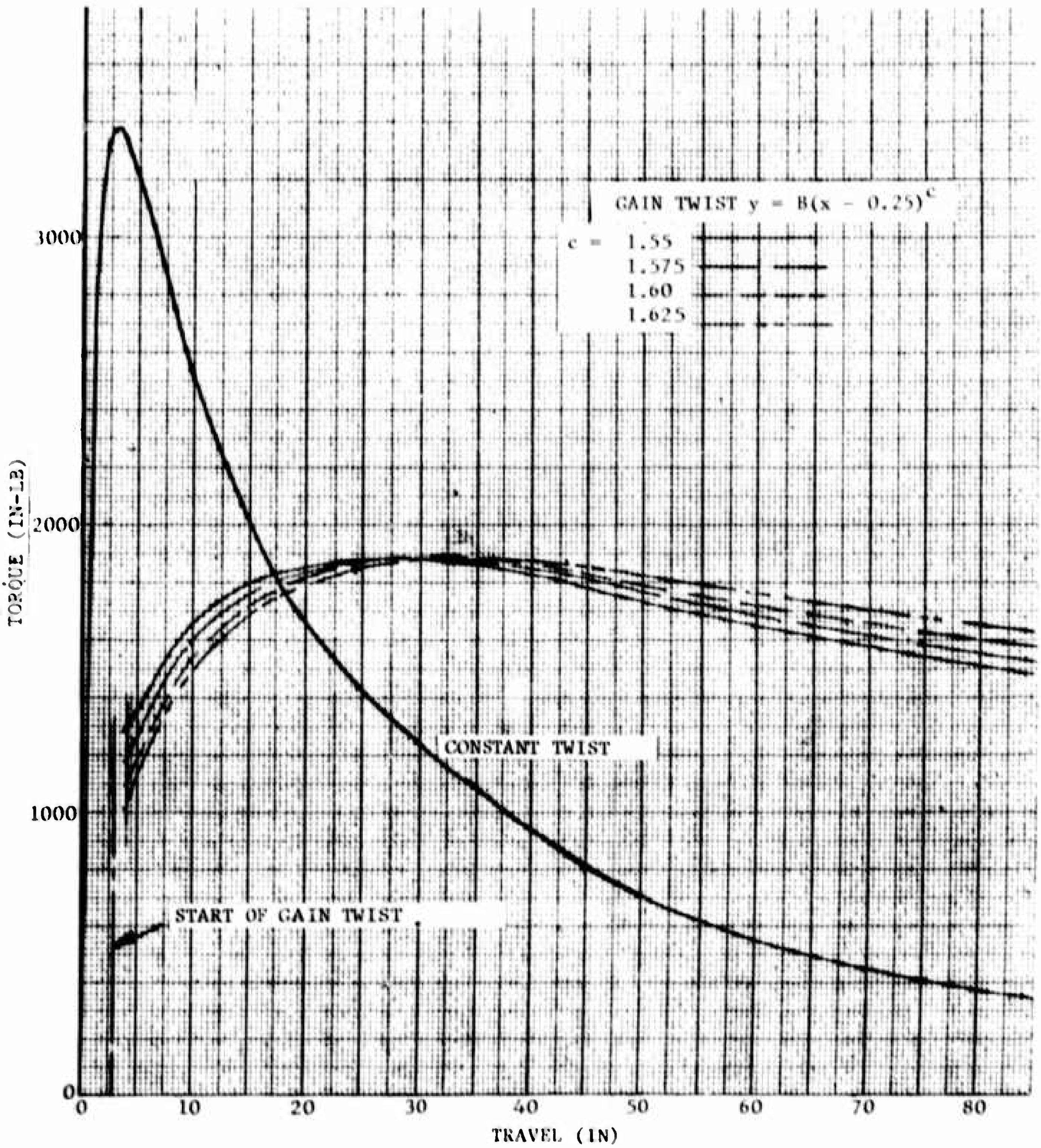


Figure 4. Torque Profile for Constant and Gain Twist Rifling (Based on EAFB Interior Ballistics)

GAIN TWIST PARAMETERS		
DISTANCE FROM START OF RIFLING (X)	ANGLE OF RIFLING	CUMULATIVE TWIST (REF)
3.0	0.00000	0.0000
3.5	0.41594	0.2161
4.0	0.64146	0.6666
4.5	0.82644	1.2883
5.0	0.98920	2.0560
5.5	1.13721	2.9547
6.0	1.27442	3.9736
6.5	1.40327	5.1047
7.0	1.52535	6.3417
7.5	1.64181	7.6794
8.0	1.75350	9.1135
9.0	1.96498	12.2561
10.0	2.16354	15.7450
11.0	2.35164	19.5605
12.0	2.53107	23.6865
13.0	2.70310	28.1098
14.0	2.86874	32.8187
15.0	3.02878	37.8031
16.0	3.18384	43.0542
17.0	3.33445	48.5641
18.0	3.48102	54.3258
19.0	3.62393	60.3327
20.0	3.76348	66.5790
22.0	4.03355	79.7687
24.0	4.29297	93.8564
26.0	4.54311	108.8092
28.0	4.78504	124.5978
30.0	5.01965	141.1965
32.0	5.24767	158.5822
34.0	5.46970	176.7341
36.0	5.68626	195.6333
38.0	5.89779	215.2624

GAIN TWIST PARAMETERS (CONT)		
DISTANCE FROM START OF RIFLING (X)	ANGLE OF RIFLING	CUMULATIVE TWIST (REF)
40.0	6.10468	235.6055
42.0	6.30726	256.6479
44.0	6.50582	278.3758
46.0	6.70063	300.7765
48.0	6.89193	323.8382
50.0	7.07990	347.5495
52.0	7.26475	371.9001
54.0	7.44665	396.8800
56.0	7.62574	422.4798
58.0	7.80216	448.6907
60.0	7.97605	475.5042
62.0	8.14753	502.9123
64.0	8.31669	530.9073
66.0	8.48364	559.4820
68.0	8.64847	588.6294
70.0	8.81127	618.3427
72.0	8.97211	648.6157
74.0	9.13108	679.4422
76.0	9.28824	710.8163
78.0	9.44365	742.7322
80.0	9.59738	775.1846
82.0	9.74947	808.1682
84.0	9.90000	841.6778

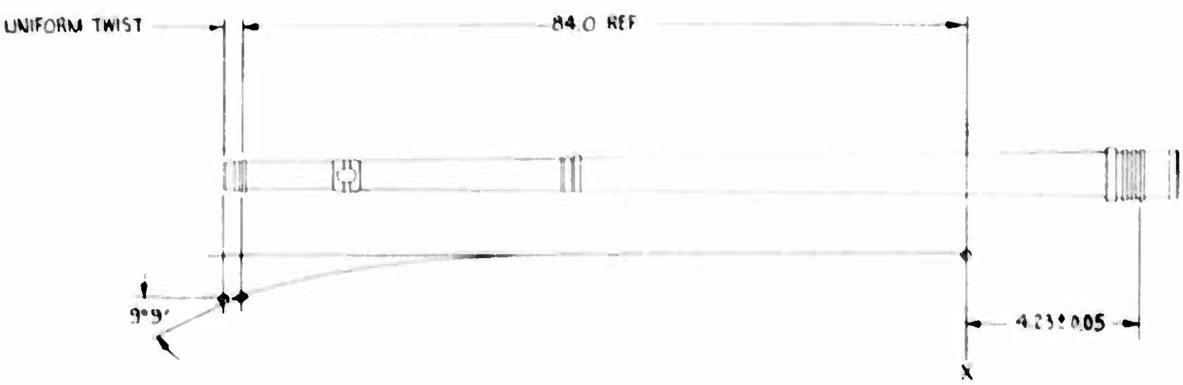
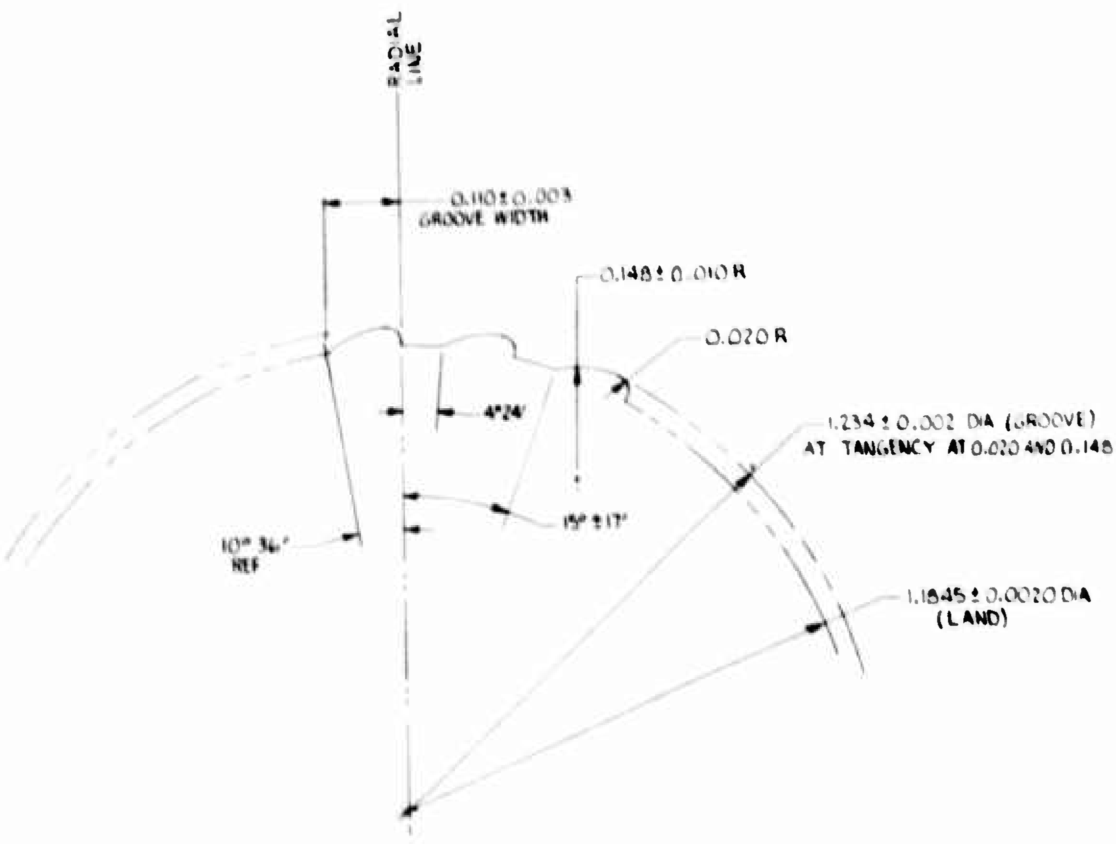
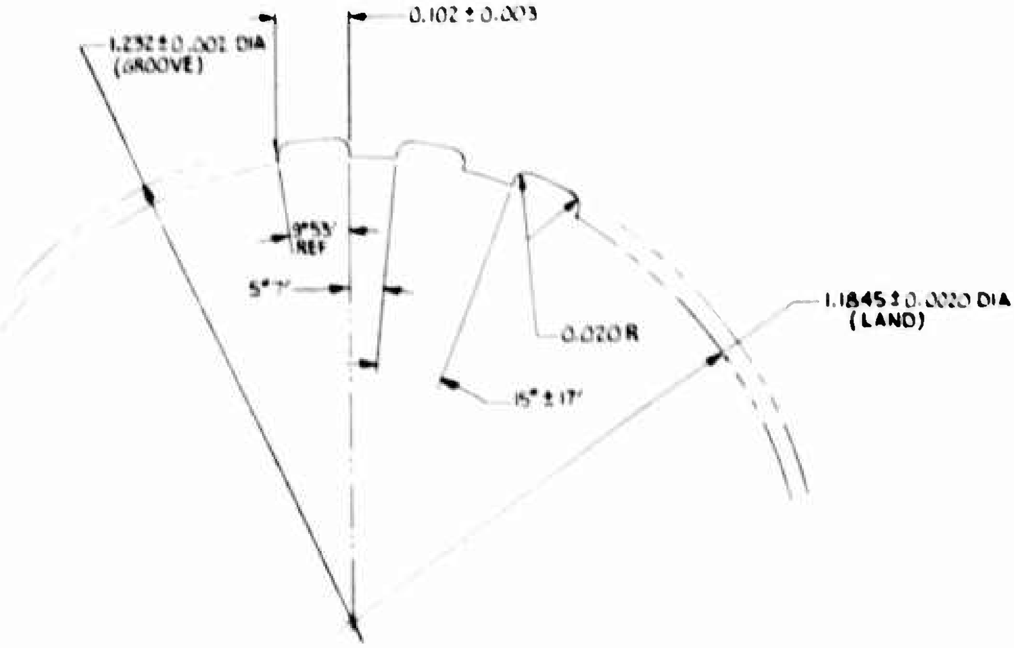


Figure 5. Twist Configuration



SAWTOOTH



MODIFIED CONVENTIONAL

Figure 6. Rifling Profile

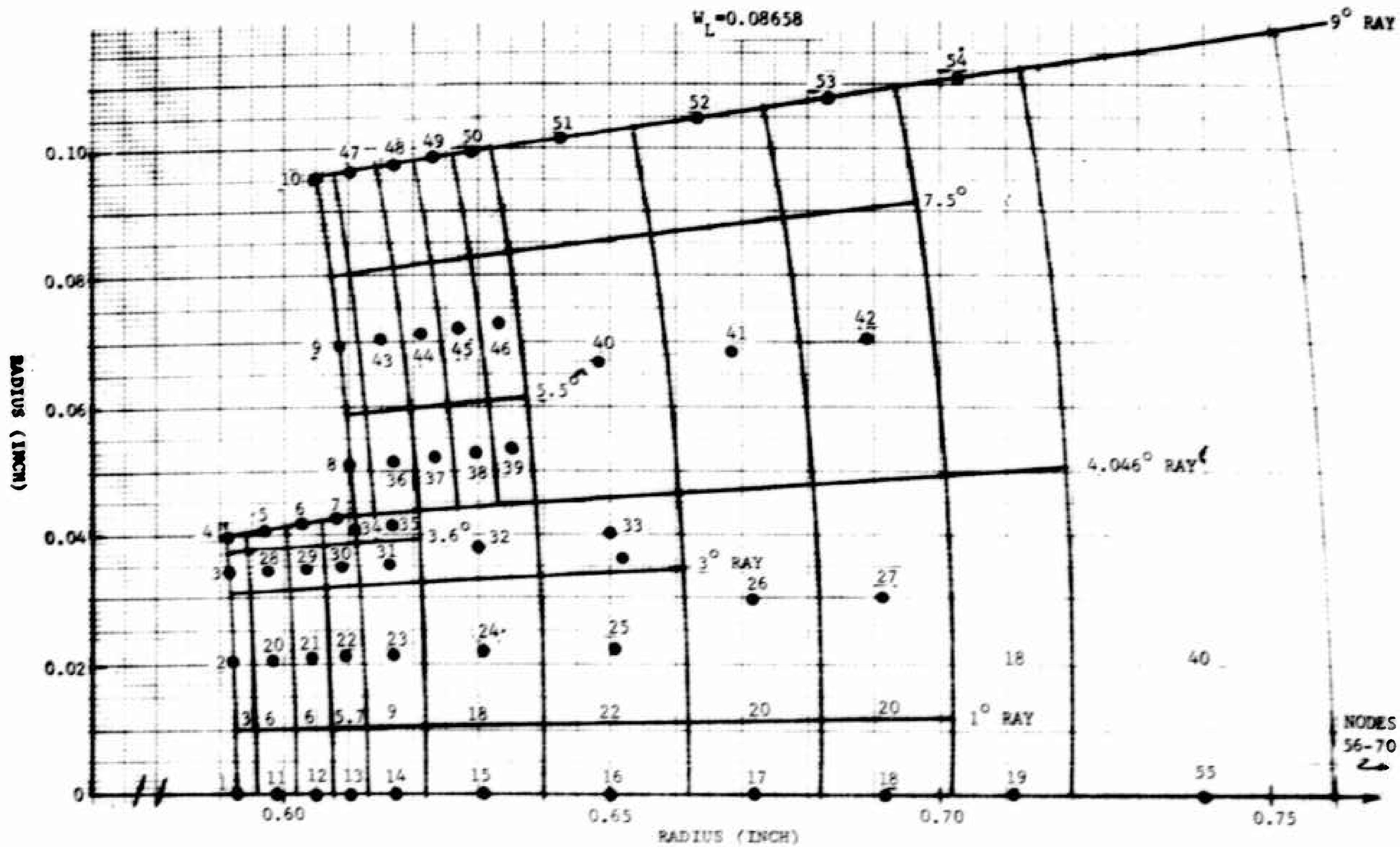


Figure 7. Two Dimensional Thermal Analysis - Nodal Matrices Conventional Rifling - 20 Lands and Grooves

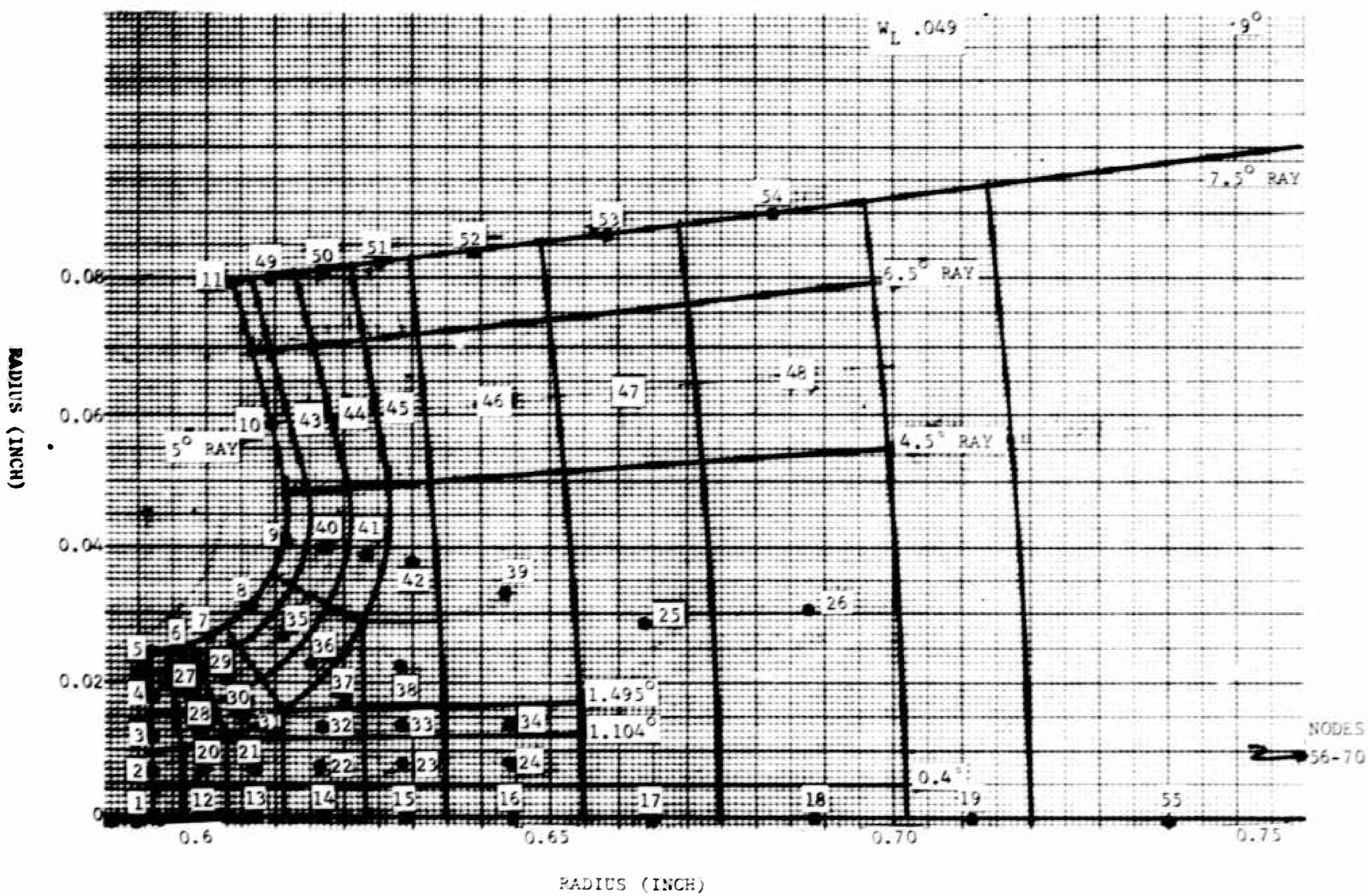


Figure 8. Two Dimensional Thermal Analysis - Nodal Matrices
Sawtooth Rifling - 20 Lands and Grooves

because of the symmetry of this configuration. It was also decided to model only the critical driving face side of the modified rifling configuration knowing that the driving side land edge would be the critical thermal point and that circumferential heat transfer along the land surface would not have a large effect. This decision was made to reduce the computational time and expense required to evaluate the thermal response under burst firing yet retaining a sufficient number of nodes.

Surface temperature histories were computed using internal convective heating parameters derived from prior Aeronutronic work with the GAU-8A weapon system. Convective heating inputs were based on Aeronutronic's 30mm GAU-8/A engineering model propellant. The grain design was a variable web thickness, 2-layer deterred configuration. Gas temperatures and convective heat transfer coefficients for this ammunition were computed with the Aeronutronic Interior Ballistics Code, ATB-4. The predicted chamber pressure history from this code indicated a close agreement with test measurements from the GAU-8/A development program.

Figure 9 shows the peak surface temperatures on the land and groove surfaces as computed for the first round in a burst. The critical location is, of course, the edge of the land. The peak temperature during the round and residual temperature at the time the next round is ignited are plotted as a function of round number in Figure 9. Comparison of these temperature histories indicated that the narrower land configurations used for both the sawtooth and modified conventional rifling will experience no worse peak or residual surface temperatures than conventional land configurations because of the generous root fillet used which improves the heat sinking path for the steep driving side of the land. It was also concluded, based upon the decided leveling trend of peak surface temperature beyond the fourth round, that no further significant information would be gained by extending the detailed two dimensional analysis further into the burst. The simplified modeling of one-half of the sawtooth land is conservative for that land configuration because the trailing side of the land has a significantly reduced exposed surface to mass ratio. The model provides nearly an exact evaluation of the modified conventional rifling configuration, however, differing only in the shape of the groove beyond the large fillet radius. Therefore, it is a justified conclusion that the narrower modified conventional land will also maintain peak and residual land edge temperatures that are comparable to the conventional 0.080 inch land width as long as the generous 0.020 inch root fillet is used.

It should be noted that a land edge radius or chamfer was not used in this comparative analysis. At the time this work was performed, there was uncertainty concerning the feasibility of achieving a controlled radius or chamfer on the land and it was concluded that a valid comparative analysis could be obtained by uniformly ignoring this feature. It is instructive to consider the very high thermal gradients that exist at the land edge, however. It is clear that introducing a 0.005 to 0.010 inch chamfer or radius on the edge will be very effective in reducing the local surface to mass ratio and the attending peak land edge temperature.

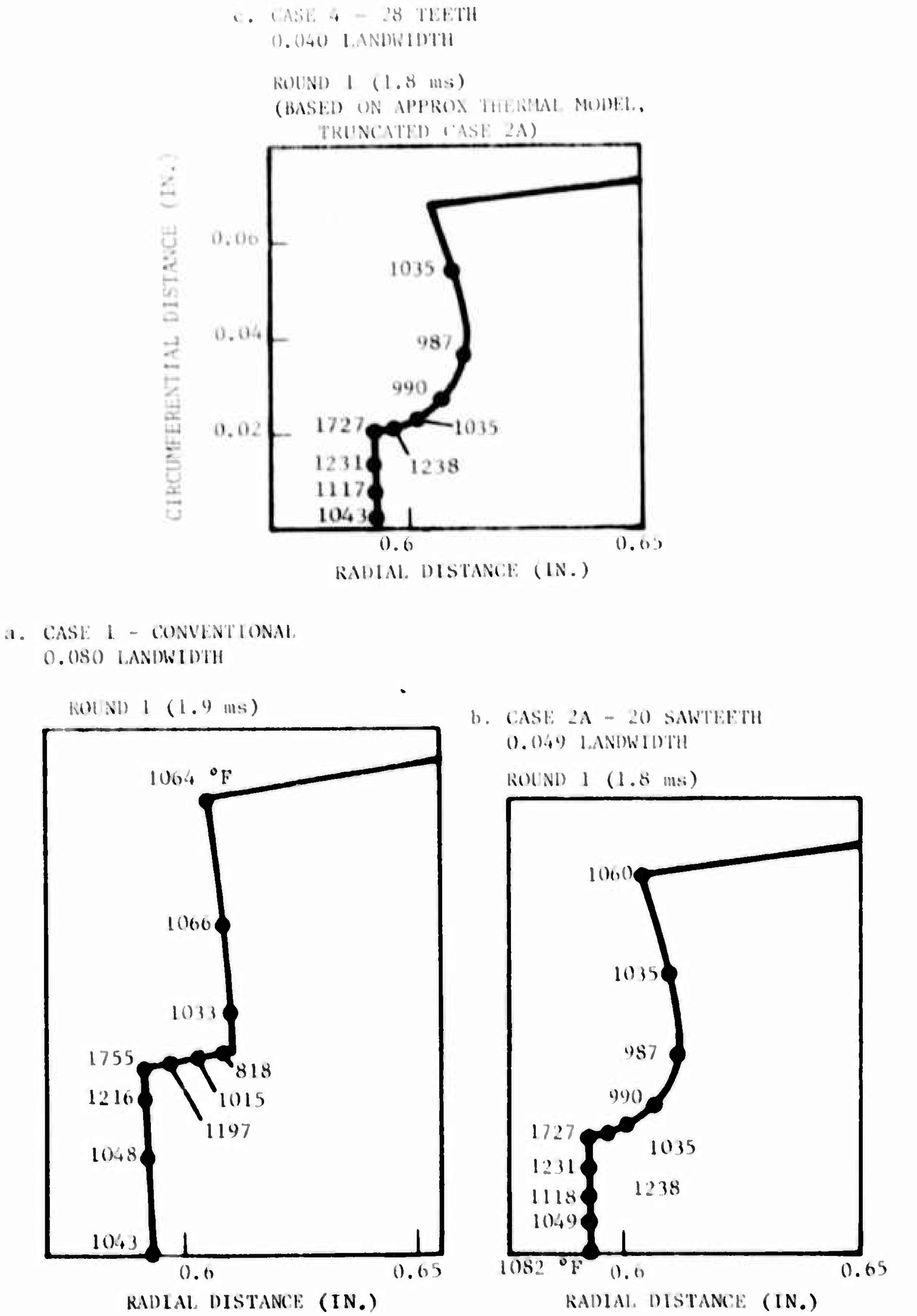


Figure 9. Peak Surface Temperatures Derived from Two Dimensional Analysis

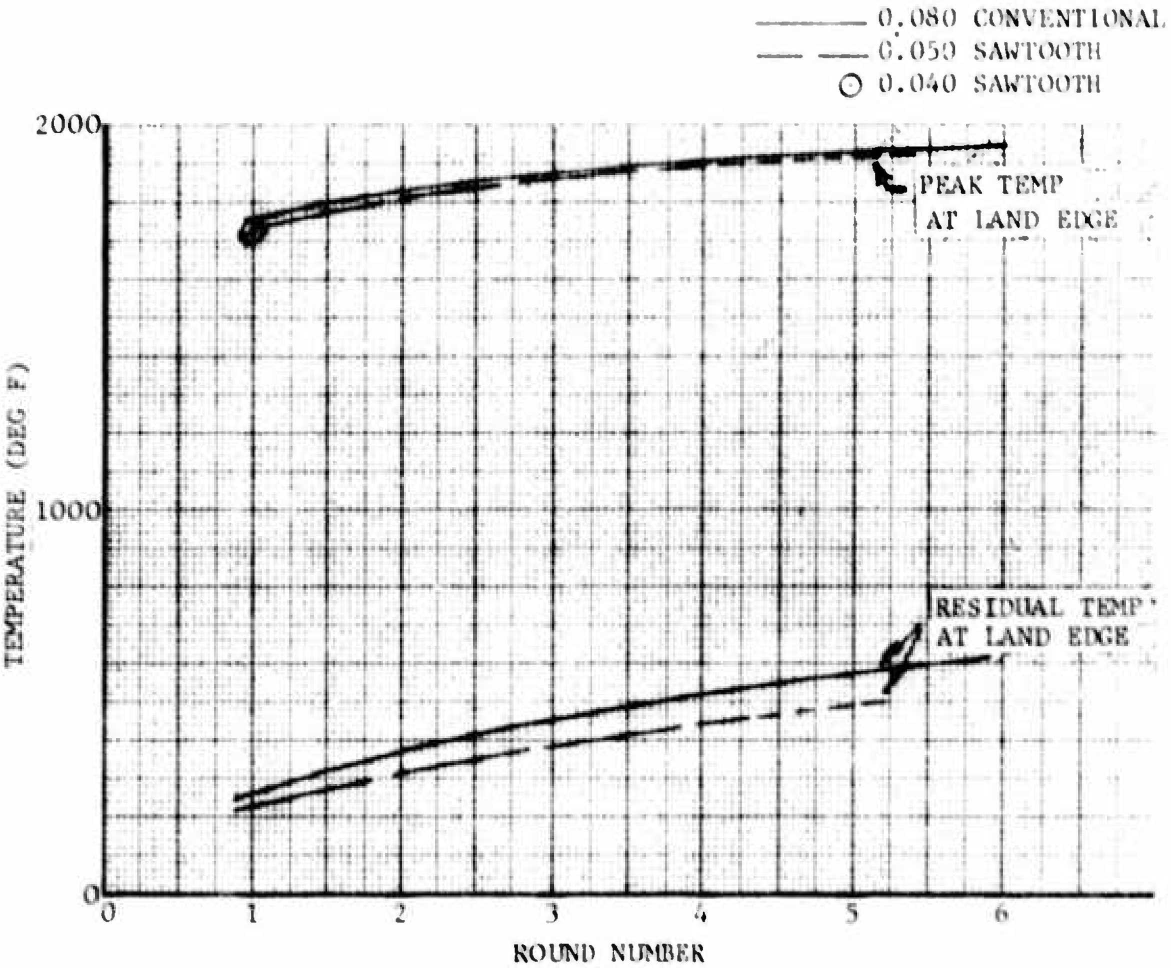


Figure 10. Comparison of Critical Land Surface Temperatures

A one dimensional barrel heating analysis was used to extend our estimate of residual bore and barrel bulk temperature for the worst case firing schedule provided by the Air Force. This firing schedule is 10 2-second bursts (about 125 rounds or 18 rounds per barrel per burst) with a one-minute cool-down between bursts.

The analysis was performed for three barrel stations to evaluate potential differences in thermal growth due to variations in barrel bulk temperature along the length. Figure 11 shows the computed trends, indicating that peak residual bore temperatures are located toward the breech but that the muzzle experiences slightly higher bulk temperatures and, therefore, thermal growth. Comparison of the magnitude of the temperature difference indicates that the differential thermal growth of the bore diameter is only of the order of 0.002 to 0.003 inch breech to muzzle. Elastic spring-back of the very highly compressed driving band should readily accommodate this small change in effective bore diameter.

2.3.2 BAND ENGRAVING CONSIDERATIONS

Review of the conventional GAU-8A rifling and candidate driving band configurations has indicated that the interference ratios, defined as:

$$IR = \frac{\text{band diameter - average bore diameter}}{\text{average bore diameter}}$$

were significantly larger than used in the 20mm plastic band optimization program or in Aeronutronic's experience in prior programs with the GAU-7 and GAU-8. It was assumed that these high interference designs were used because of some helpful interaction with the mechanical retention and torque transmission interface between the band and projectile. An attempt was made, however, to evaluate the relative engraving pressure levels and to evaluate the tendency of the band to extrude longitudinally during the engraving process.

The initial effort was analytical using the theoretical equations to evaluate the pressures exerted on the band. These engraving pressure equations are recognized to be unverified for use with plastic band materials but were used to get a feel for the relative engraving loads for the two candidate band configurations and how these loads might vary with rifling configuration. The engraving pressure P is normalized by the yield stress of the band material and related to key rifling and band physical dimensions using the equation:

$$\frac{P}{y} = \frac{2}{\sqrt{3}} \; \frac{W_L}{W_L + W_G} + \frac{L}{2\sqrt{3}\,t}$$

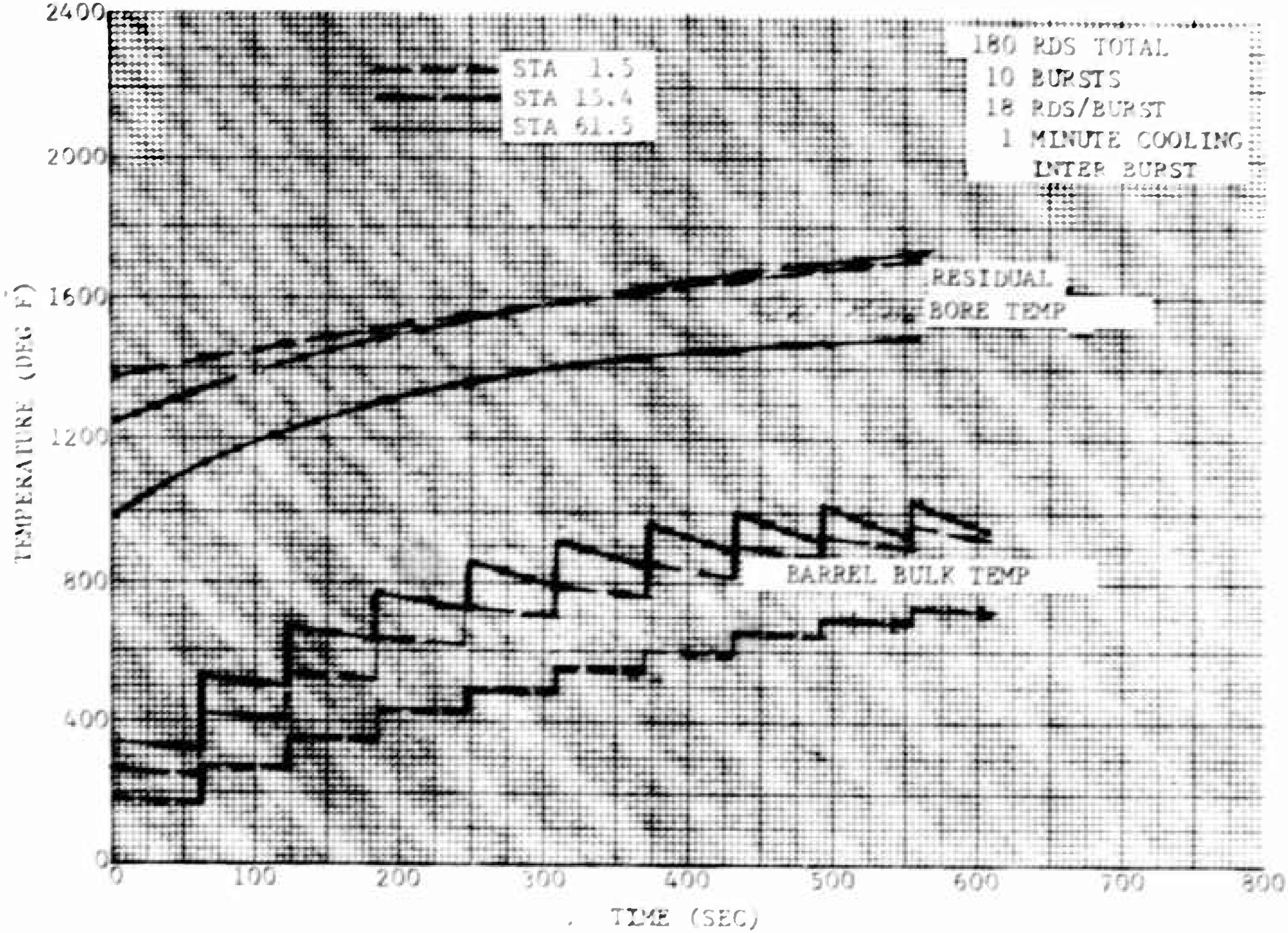


Figure 11. One-Dimensional Barrel Heating
Trends for 18-10-1 Min Schedule

where:

W_L is the rifling land width

W_G is the groove width

L is the final extruded band length

t is the average band thickness

In this case it is difficult to define what band thickness to use because the extruded material extends beyond the band seat. For this comparative analysis the thickness was assumed to be the difference between the mean bore radius and the projectile radius over which the material was extruded.

Figures 12 and 13 indicate the variation of the mean bore diameter for a range of sawtooth and modified conventional rifling parameters. For reference the mean bore diameter of the current GAU-8 rifling design with 20 lands and grooves is 1.208 inches. These data relate directly to the subsequent computation of relative engraving pressure primarily through the influence on the final extruded length and thickness of the driving band; that is, small mean bore diameters yield high relative engraving pressures. These pressure trends are shown for both rifling types and band candidates in Figures 14, 15 and 16. Comparing the data from these figures and relating to P/y studies from the 20mm rifling optimization study leads to the following observations:

- The P/y levels are much higher than those experienced with the 20mm configuration (two to 10 times greater).
- The long driving band experiences signficantly higher extrusion stresses even though the band diameter is 0.010 inch less than the diameter of the narrow bands of the other candidate. This could be a particular problem for cold soak temperatures.
- Increasing the number of lands and grooves should be accompanied by increases in groove depth or reductions in land width to preclude excessive band extrusion.

Referring to Figures 12 and 13 mean bore diameters in the region of 1.21 to 1.212 were considered desirable.

2.3.3 FINE CODE ANALYSES

Finite element structural analysis has proven to be an effective tool for evaluation of alternate rifling configurations. Analysis of the plastic rotating band indicates the magnitude of induced stress in critical areas which typically are located at the driving interface with the land and the torque transmitting interface with the projectile. Barrel stress analysis

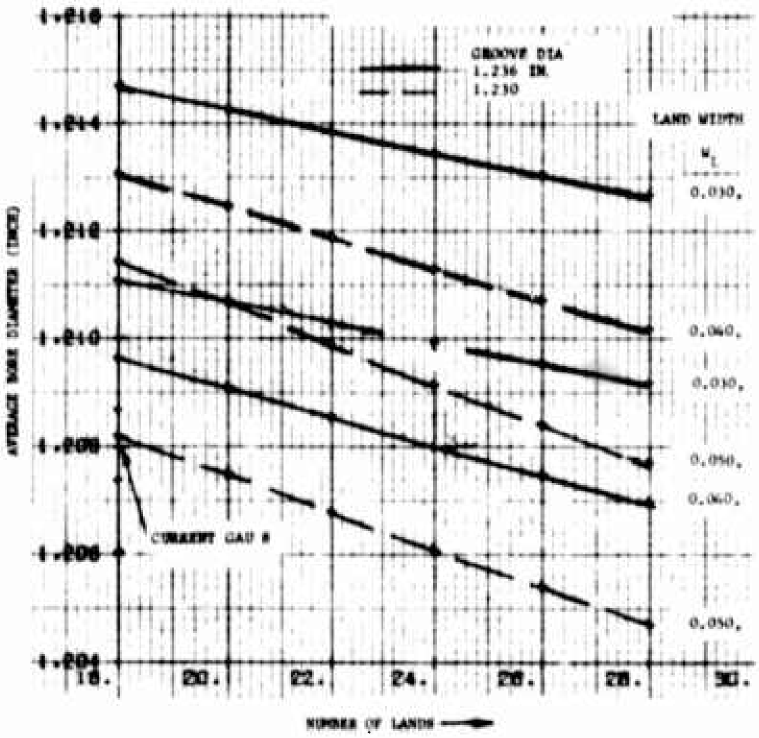


Figure 12. Variation of Mean Bore Diameter with Rifling Parameters - Sawtooth

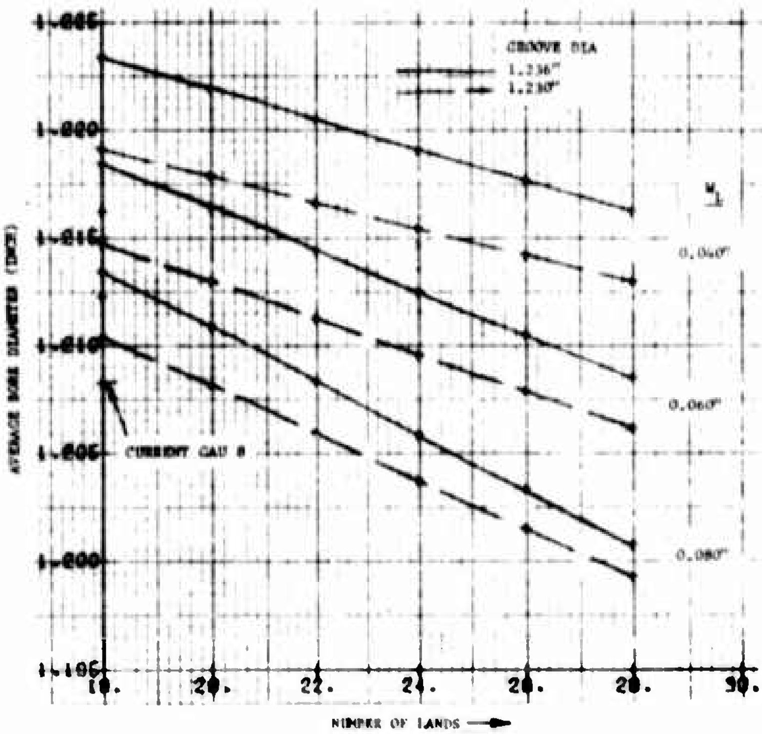


Figure 13. Variation of Mean Bore Diameter with Rifling Parameters - Modified Conventional

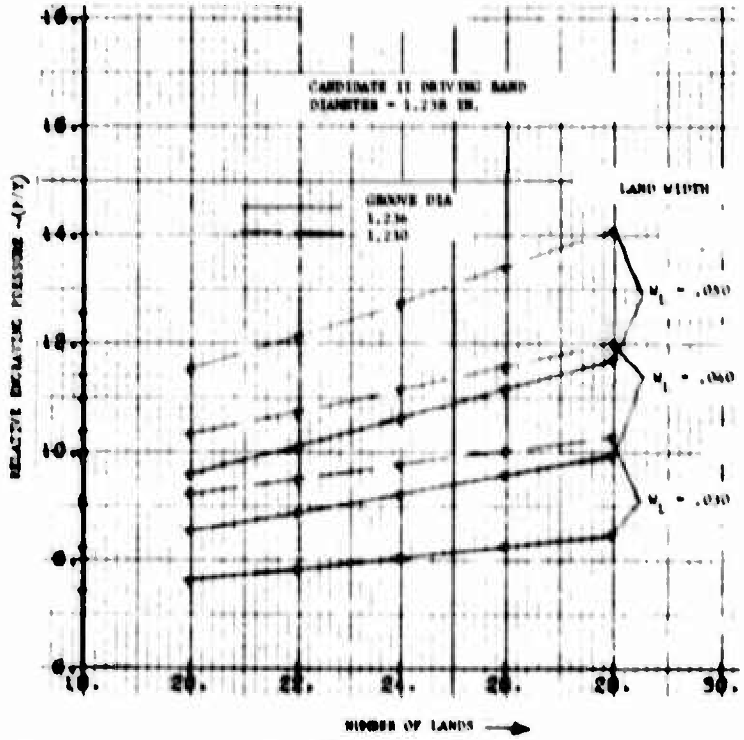


Figure 14. Relative Band Engraving Pressure
Sawtooth Rifling

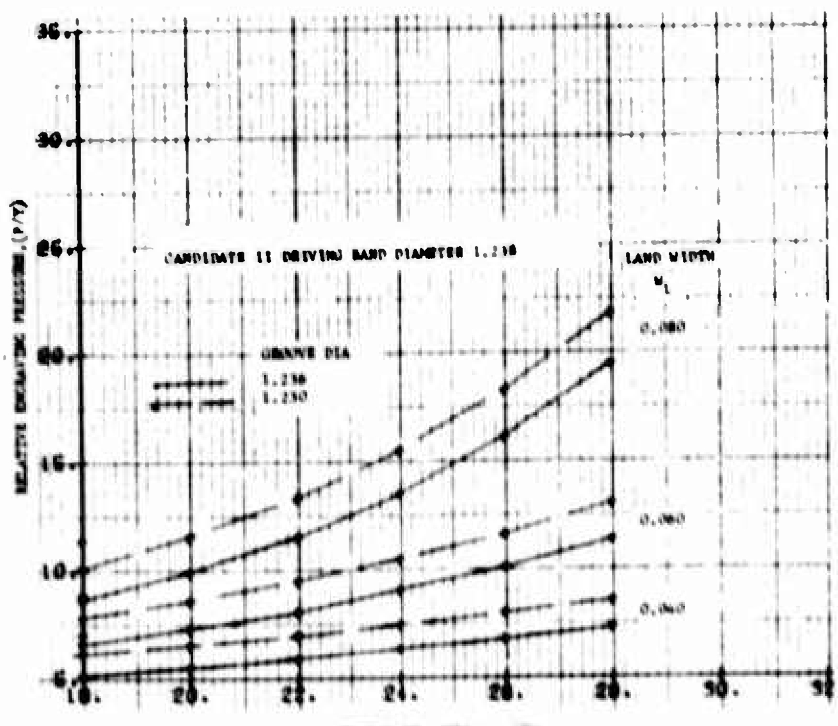


Figure 15. Relative Band Engraving Pressure
Modified Conventional Rifling

CANDIDATE I. DRIVING BAND DIA = 1.228 INCH

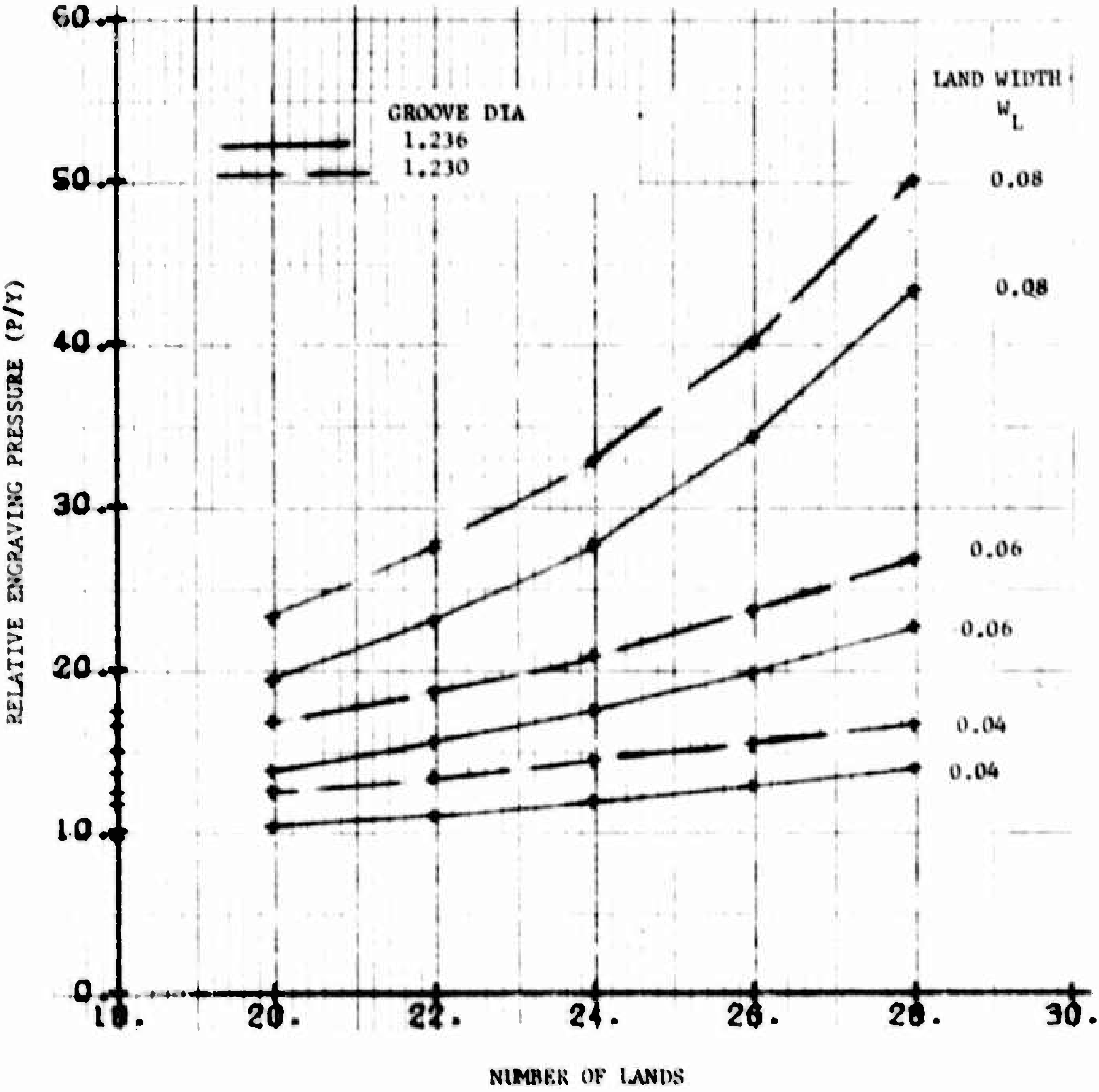


Figure 16. Relative Band Engraving Pressure Modified Conventional Rifling

is directed at evaluating stress concentration effects generated by the land and groove profile when the barrel is subject to the combined effects of pressurization and torque loading.

The prior application of the Aeronutronic FINE computer code for rifling stress analysis considered arbitrary uniform and triangular torque pressure distributions on the driving surface of the land and band. A plane strain analysis, which models the band as an infinite cylindrical segment was selected as providing meaningful comparative results yet avoiding the gross complexity of full three dimensional simulation.

The first task undertaken in this program was to establish a realistic torque loading profile for the lands. This was accomplished through use of an alternate modeling technique illustrated in Figure 17. Prior analyses considered the band to be constrained at the projectile interface and loaded at the land driving surface by the arbitrary pressure distribution. The alternate loading assumes a radial constraint only at the band interface with the projectile and adds a distributed uniform torque load at the interface equal to the required peak spin-up torque. The driving face of the engraved band surface was then assumed to be bounded by radial constraints and the resultant stresses in the tooth surface region analyzed to evaluate the induced surface pressure profile.

Figure 18 depicts tooth surface pressure profiles derived from extrapolation of elemental stress profiles out to the tooth surface. One curve is based upon extrapolation of the RSS of hoop and radial stress components and the other based upon the minimum stress component which is basically the magnitude of the compressive stress. The extrapolation was based upon cross plots of these stress components versus distance from the surface for constant "J" in the mesh matrix as illustrated in Figure 17. Based upon the results of Figure 18 it was concluded that a truncated triangular torque pressure distribution as a function of percent of groove depth would provide an adequate representation for subsequent analysis of bands and barrel.

A typical analysis configuration and results for a sawtooth rifling configuration is illustrated in Figures 19 through 22. The specific profile illustrated is the baseline sawtooth configuration impressed upon the Candidate II band. The judgments concerning preferred rifling profile configuration were based primarily upon evaluation of the Von Mises equivalent stress σ_{eq} and the shear stress (τ) levels in the stress fields of the middle torque driving face of the three-land segment. This region is selected to avoid the effects of imperfect modeling of the ends of the band segments. Maximum stress levels typically occurred in the band region adjacent to the pressure-side land edge. In addition, the maximum σ_{eq} and shear stress induced at the band interface were evaluated and compared for varying tooth shape parameters. Figure 22 shows a typical stress plot at the projectile interface. A similar set of FINE code plots are provided for the baseline modified conventional rifling configuration and Candidate II band in Figures 23 through 26.

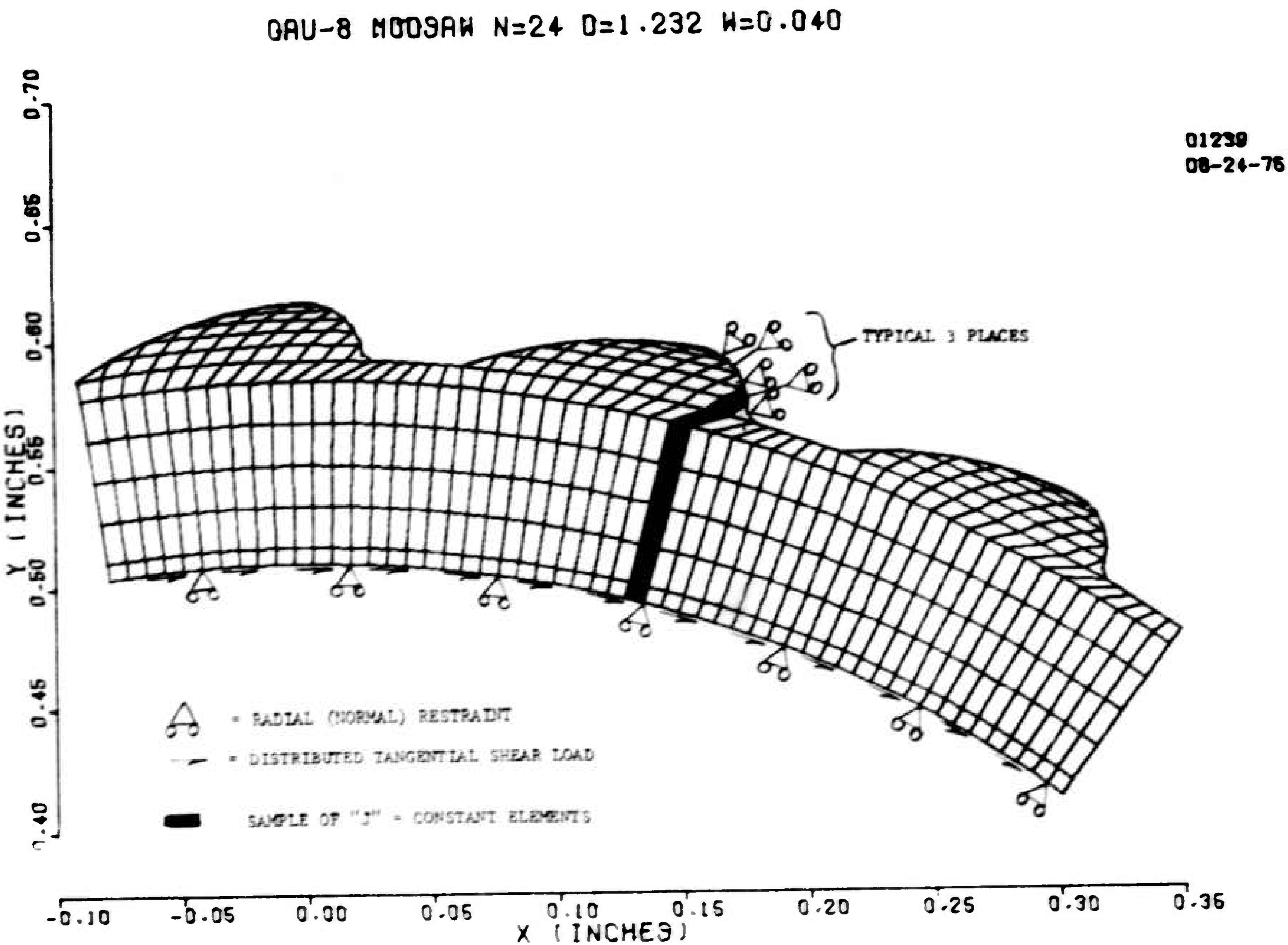


Figure 17. Mesh Plot and Alternate Loading Definition

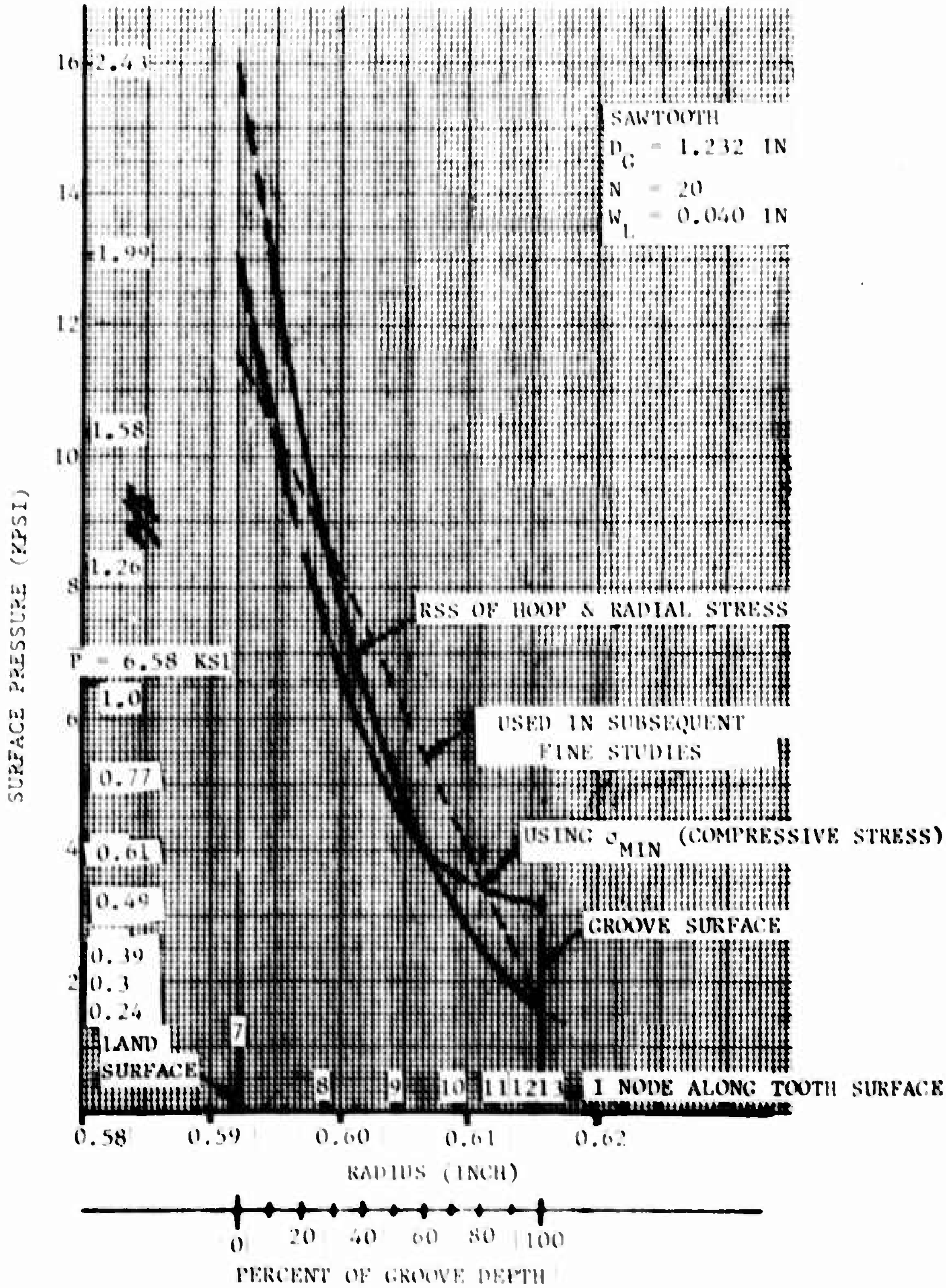


Figure 18. Computed Tooth Pressure Distribution

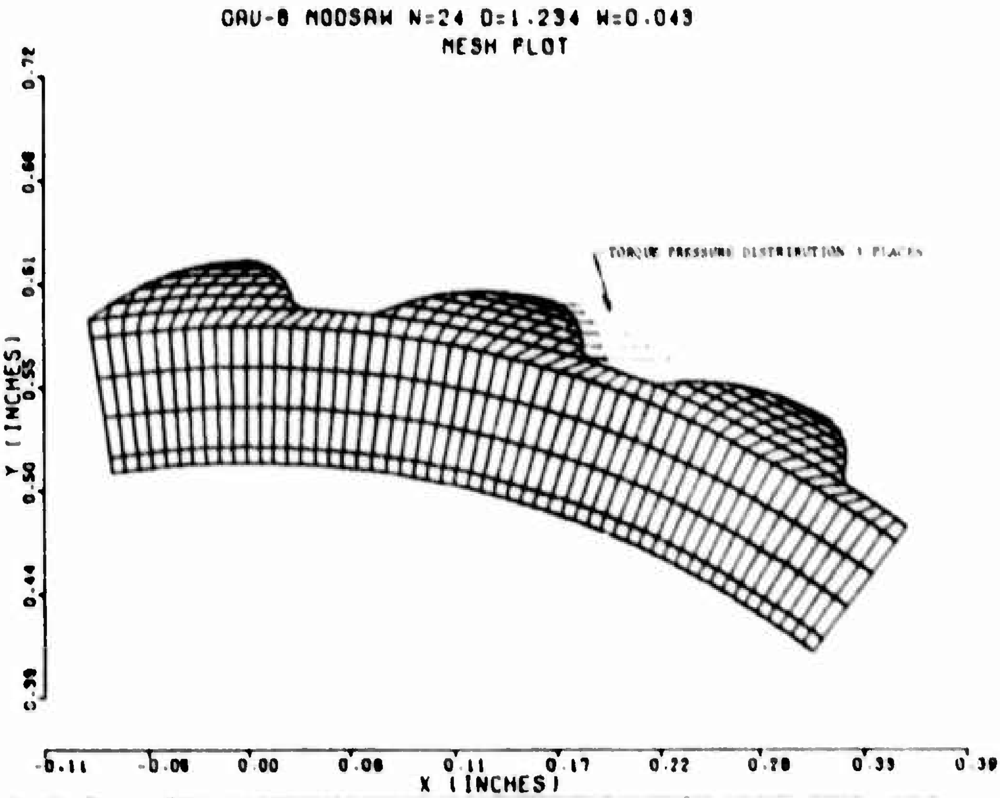


Figure 19. Typical Sawtooth Mesh Plot

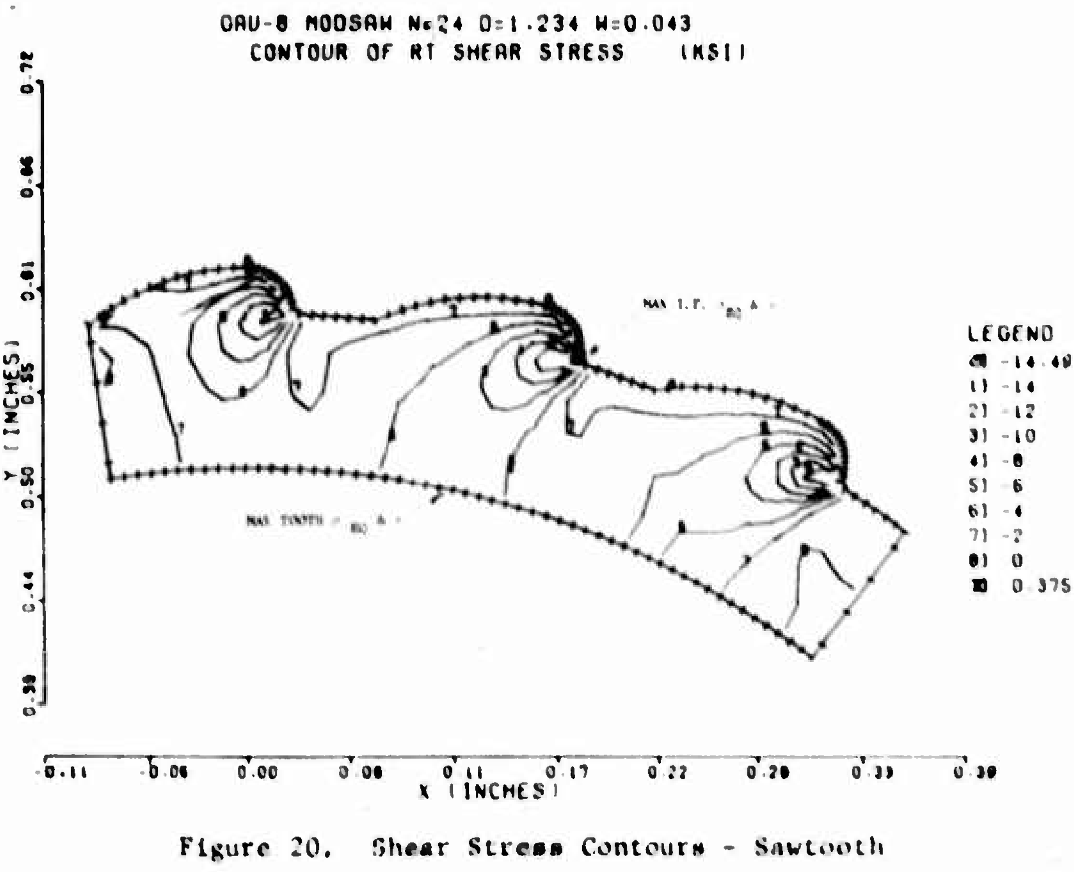


Figure 20. Shear Stress Contours - Sawtooth

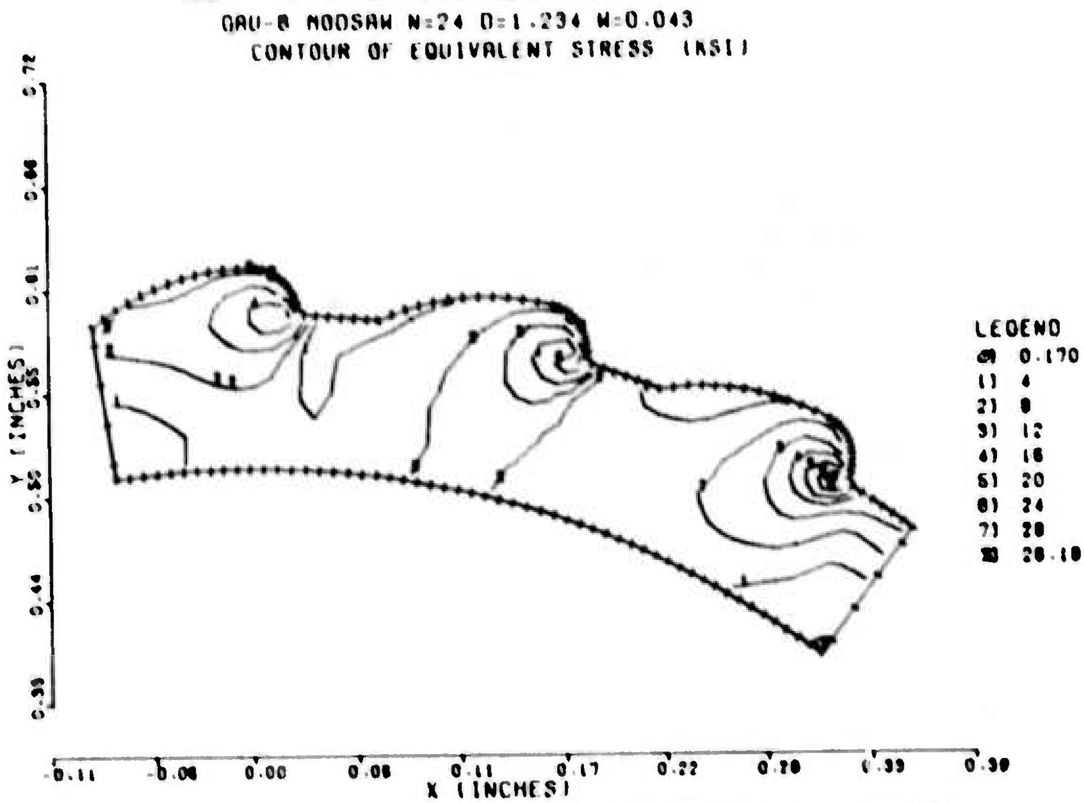


Figure 21. Equivalent Stress Contours - Sawtooth

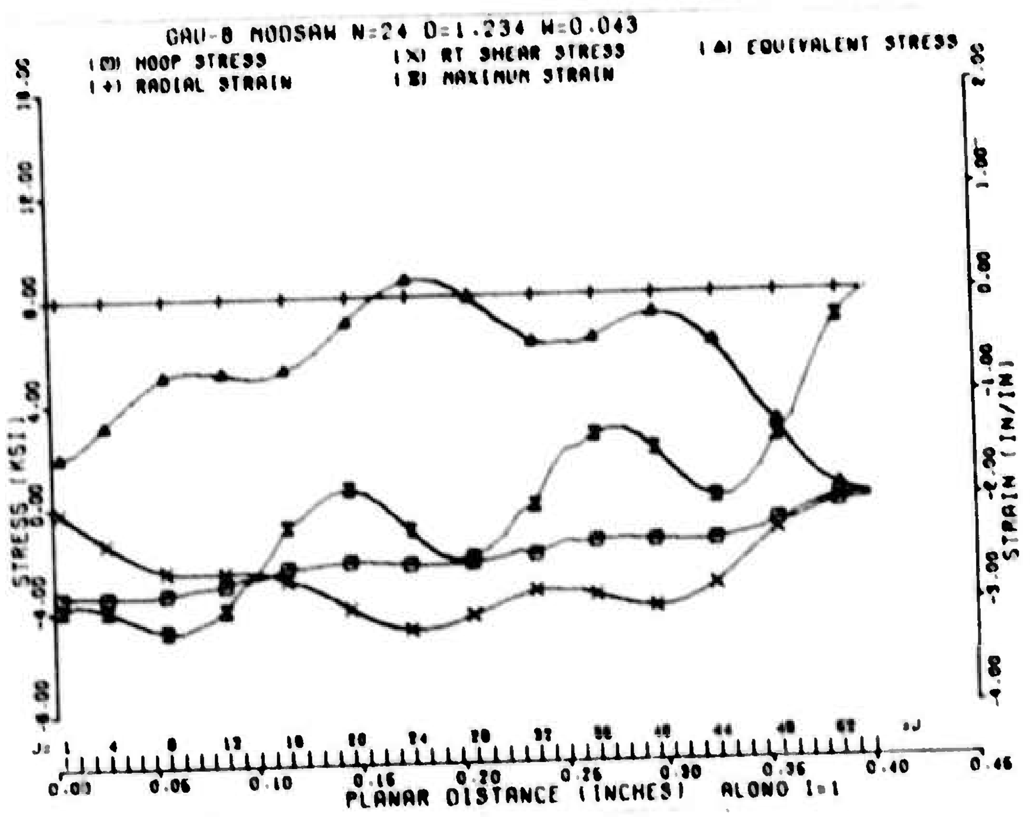


Figure 22. Stress Distribution at Band - Projectile Interface

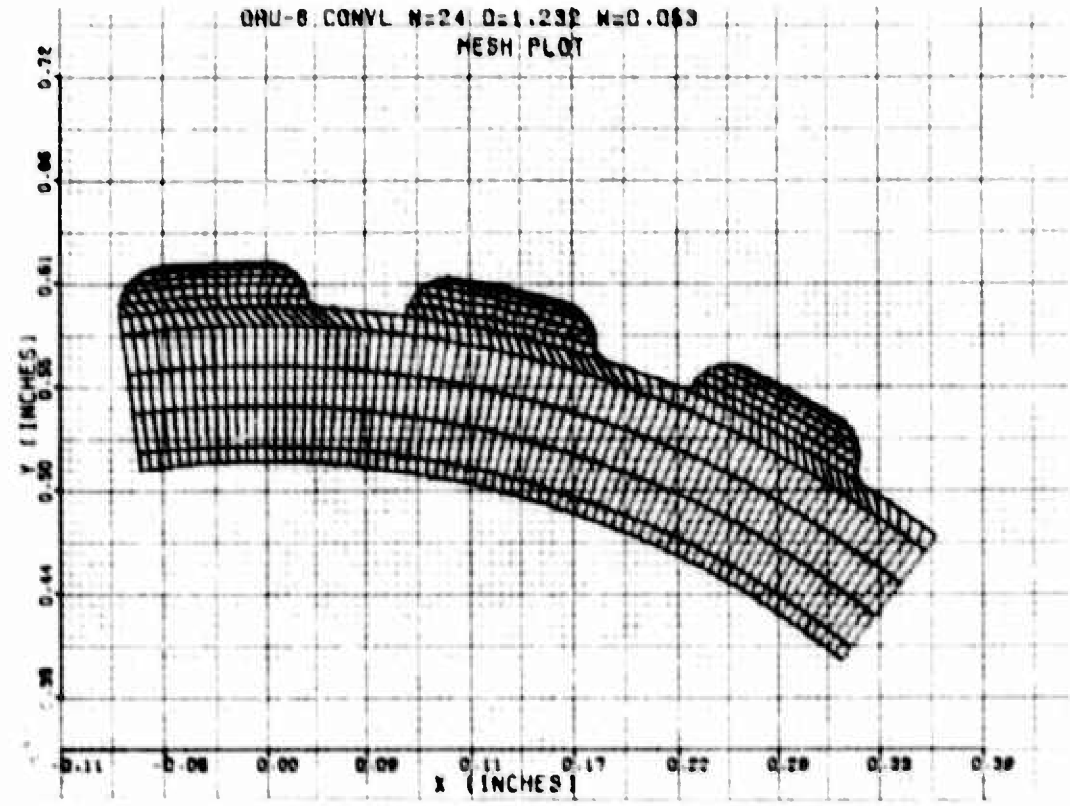


Figure 23. Typical Mesh Plot - Modified Conventional Rifling

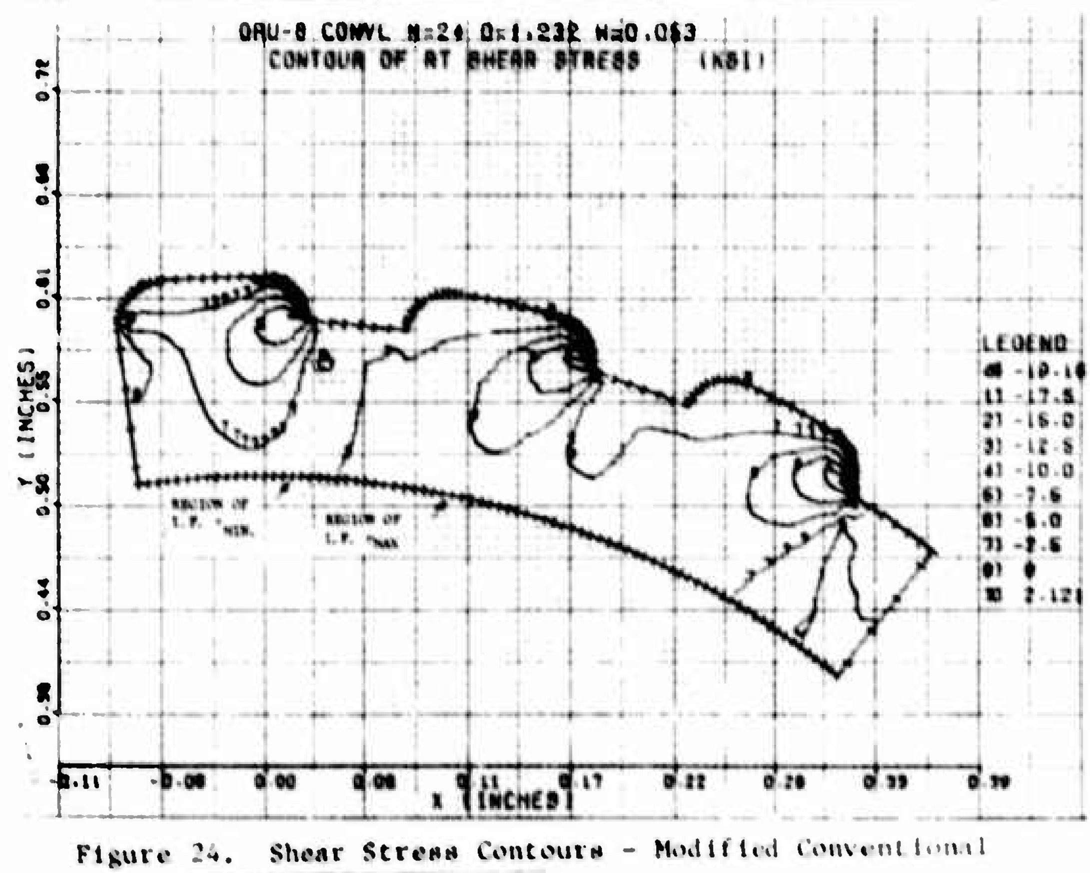


Figure 24. Shear Stress Contours - Modified Conventional

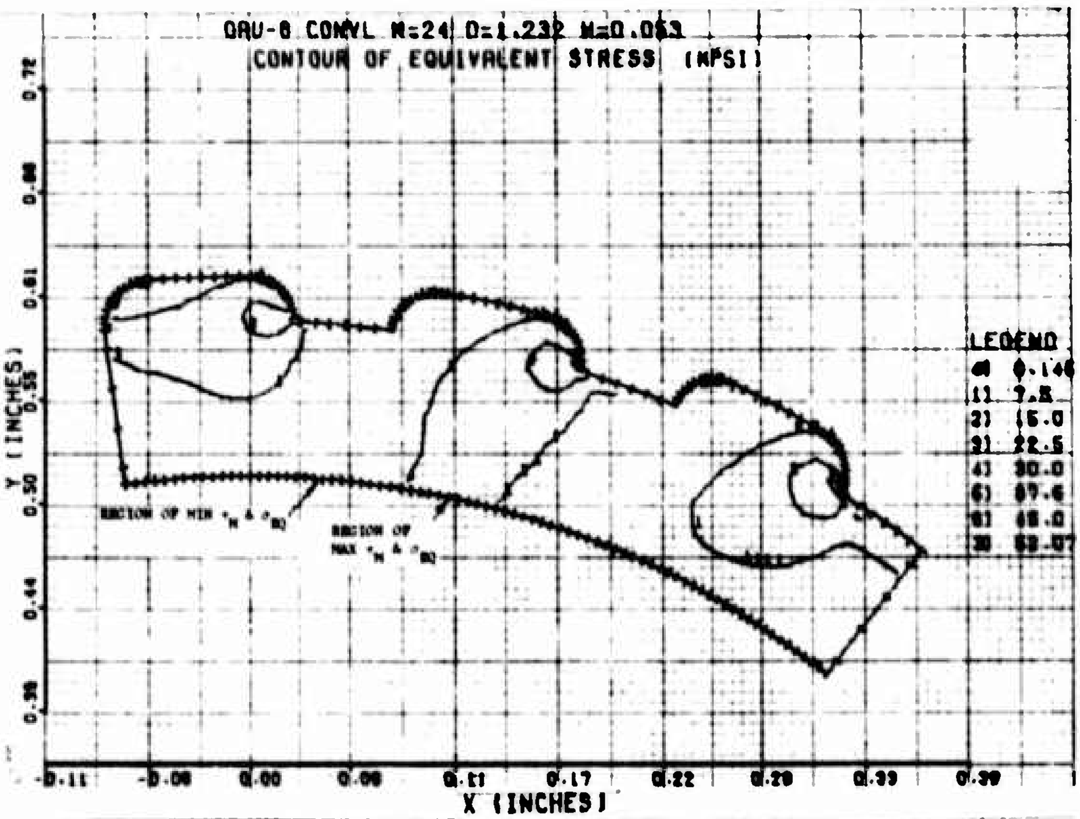


Figure 25. Equivalent Stress Contours - Modified Conventional

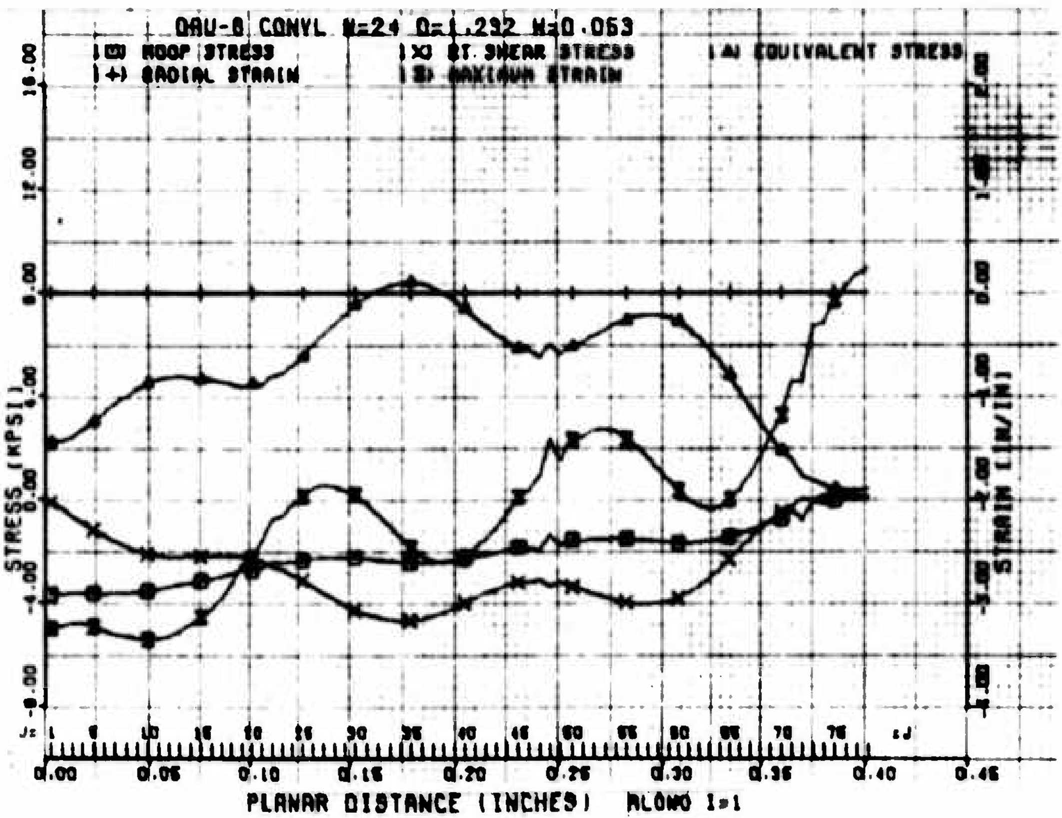


Figure 26. Stress Distribution at Band - Projectile Interface

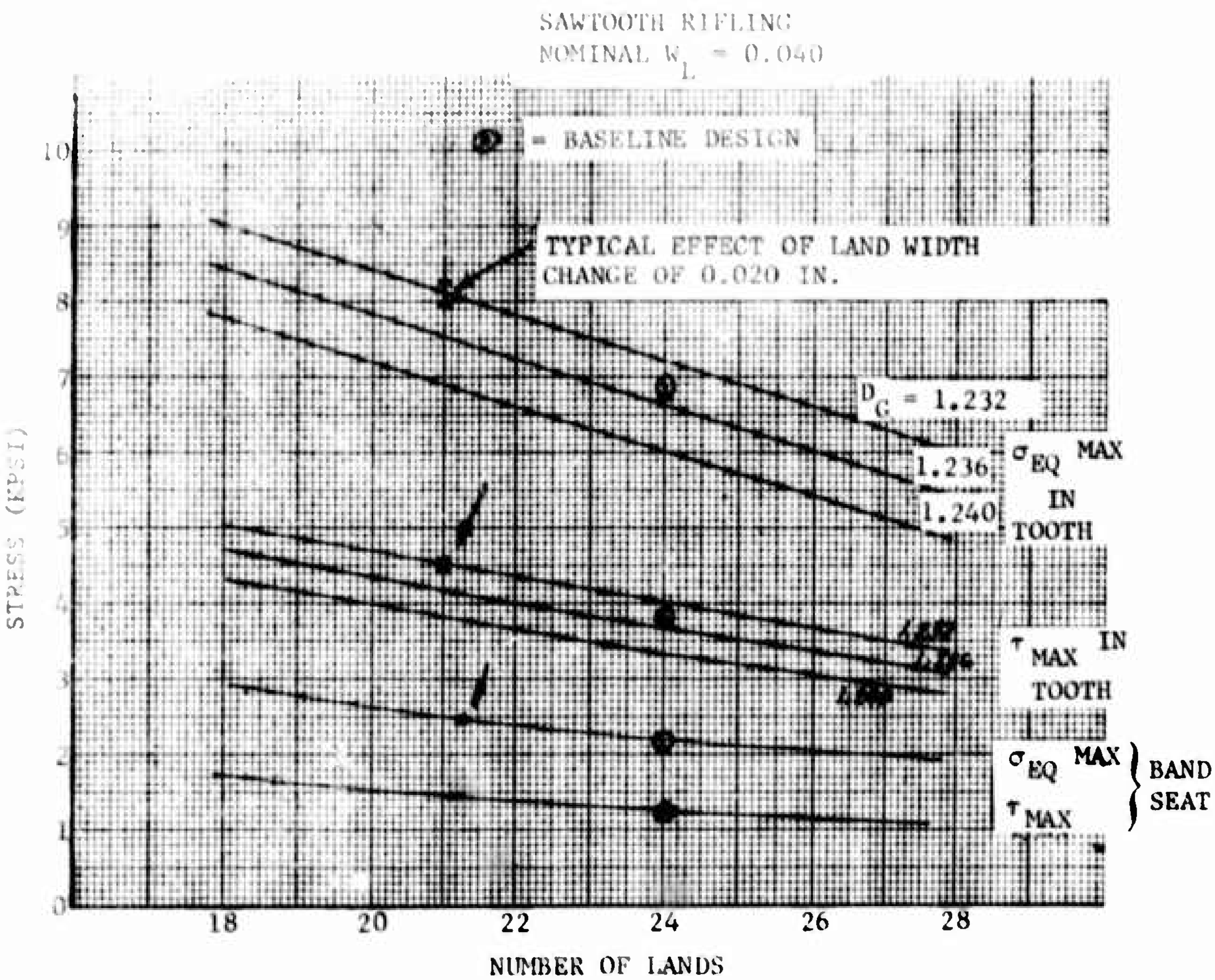
The rifling shape parameters and the range over which these parameters were varied in this study are as follows:

Parameter	Parameter Range	Current GAU-8
Number of Lands and Grooves	18 to 26	20
Groove Diameter	1.226 to 1.240	1.226
Land Width	0.32 to 0.070	0.080
Root Fillet Radius	0.020	0.007
Sawtooth Groove Radius	0.14 to 0.20	--

Figure 27 summarizes the results of the band stress studies for the sawtooth profiles using the FINE code. In general it can be stated that increasing the number of lands and grooves improves the circumferential torque loading distribution in the bands with an attending reduction in stress both at the barrel interface and at the projectile (band seat) interface. Also, an increase in groove depth reduces the per unit area loading on the driving face and tends to reduce the local peak equivalent and shear stress levels in the band. Reasonable variations of groove radius parameters and land width parameters were found to have very minor effects on band stress due to torque loads.

Similar but less extensive analyses were done for the modified conventional rifling which were then compared with the sawtooth results in Figure 28. It can be seen that a comparable number of lands and groove depth results in a small increase in the computed stress levels in the vicinity of the engraved tooth but that the stress levels at the band seat are essentially unaffected. The design point for both the sawtooth and modified conventional rifling configurations are spotted on these curves.

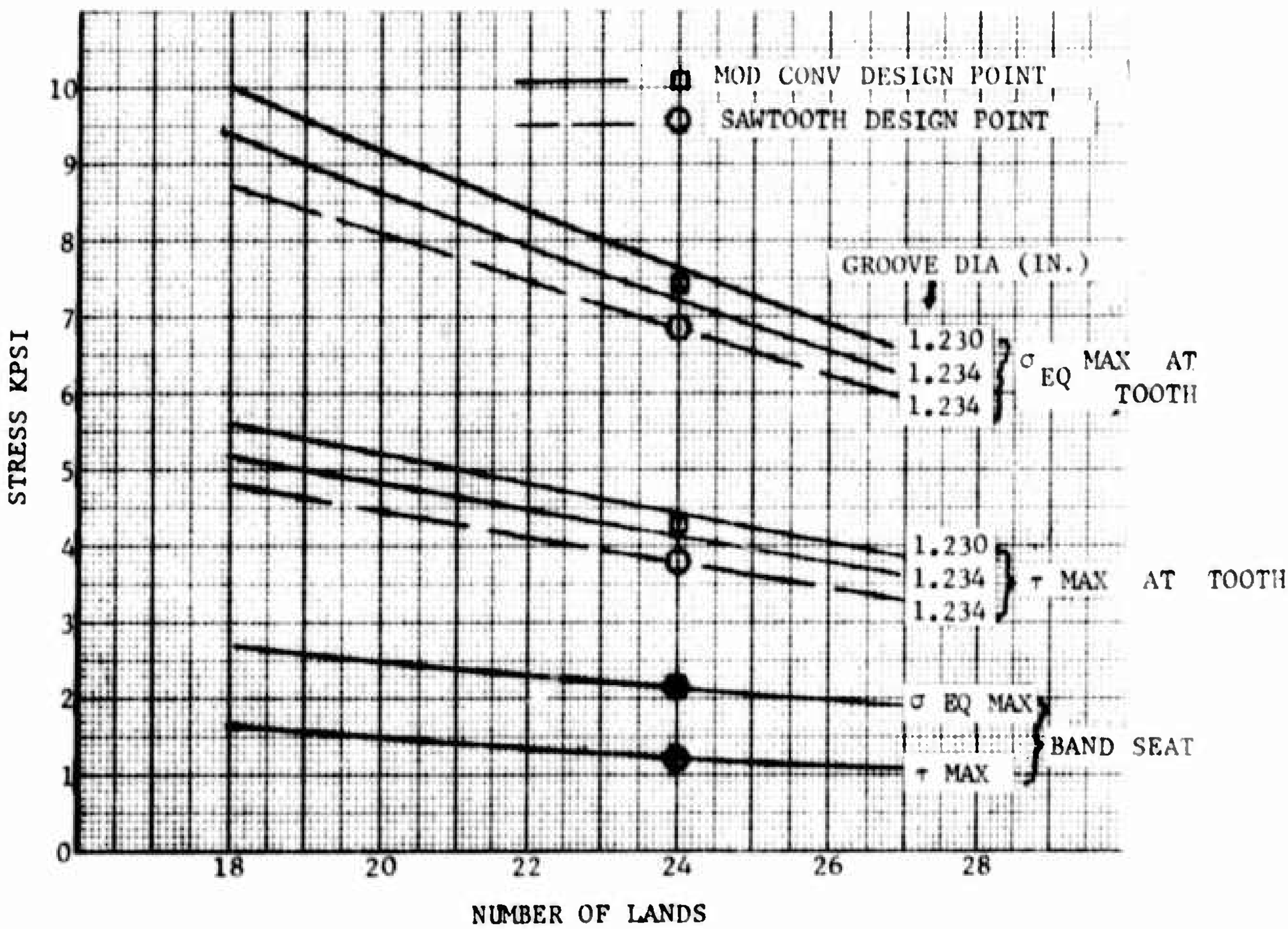
Most of the rifling shape parameters were explored with respect to their impact on band stress. Based upon prior 20mm barrel analysis a conclusion was reached that barrel stress would be minimized for configurations which tend toward rectangular grooves and have minimum land width. Limitations of land width are dictated by thermal considerations discussed above. The reason for the reduced stress for the rectangular groove configuration apppears to be that the narrower land root of the modified conventional land versus the sawtooth land causes less displacement of the hoop stress contours into the land region and, therefore, yields less stress concentration in the groove region. This can be readily seen in comparing the hoop stress contours for typical sawtooth and modified conventional profiles in Figure 29.



NOTE: SAWTOOTH GROOVE SHAPE PARAMETER CHANGES GIVE SMALL STRESS EFFECTS.

BASELINE GROOVE DIA SET AT MAXIMUM COMPATIBLE WITH CHAMBERING AND PLATING CONSTRAINTS.

Figure 27. Summary Stress Trends



NOTE: MOD CONVENTIONAL LAND WIDTHS 0.050 TO 0.060 IN.

Figure 28. Comparison of Band Stress Levels Induced by Modified Conventional and Sawtooth Rifling Profiles - Torque Loading

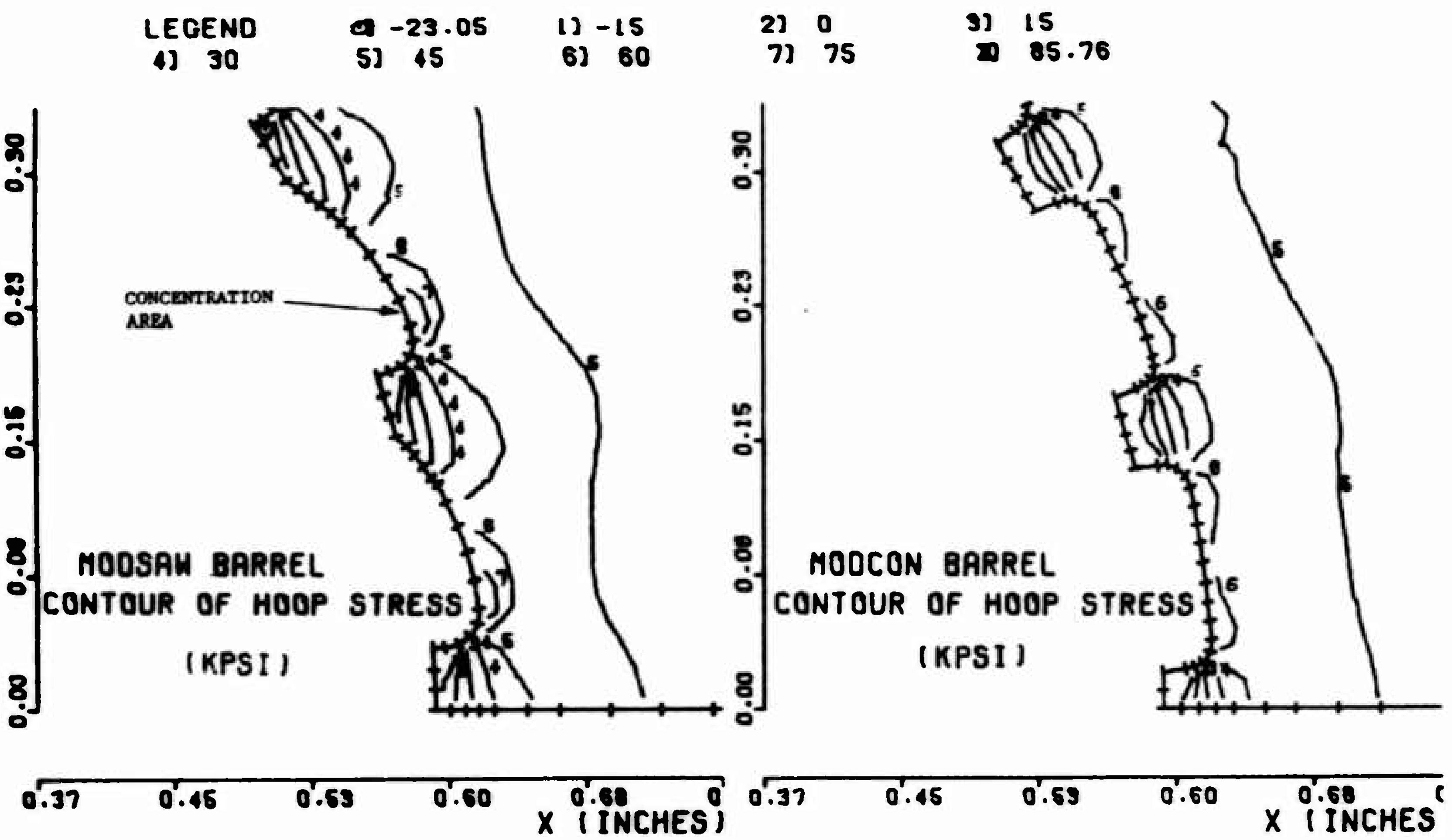


Figure 29. Hoop Stress Concentration Comparison of Sawtooth and Modified Conventional Rifling

Studies of barrel stress encompassed the cases summarized in Table 3. The cases were selected to explore the criticality of different barrel stations, the effects of varying the number of lands and the depth of groove, and to compare the stress magnitudes for sawtooth and modified conventional rifling profiles. The barrel internal pressure levels used were as derived from the representative interior ballistics data of Appendix A. A peak torque loading distribution on the lands was assumed equal to that shown in Figure 18 for one comparative case to ascertain the magnitude of the torque pressure effect. Comparisons were made of maximum equivalent stress at the point of maximum concentration on the bore surface and at a radial distance of 0.742 inch from the bore centerline or about mid-wall thickness at barrel station 23.0. These comparisons were made by extrapolation/interpolation of radial stress plots for each configuration. The trend data are summarized in Figure 28. The equivalent stress differences induced by the shape change variations in the sawtooth profiles are seen to be of the order of ±2 percent both at the bore surface and at the 0.742 inch radial location at station 23.0.

The difference in stress levels for the modified conventional configuration versus the sawtooth is seen to be approximately 12 percent and there is very little difference in bore stress levels for the small variations in groove diameter and land width explored with the modified conventional configuration.

The very conservative model of superimposing a torque pressure equivalent to that induced on the band is shown to increase the peak equivalent stress in the bore by about 3 percent. This model is extremely conservative because the torque loading is very local (i.e., over the length of the band) whereas the plane strain barrel analysis assumes the torque load is continuous over the length of the barrel. End effects will significantly reduce the stress increment from that computed.

The barrel analysis lead to the following observations:

- Reasonable variations of configurations of a given rifling design have negligible impact on computed stress levels (excluding sharp root fillets). The trend is that reducing the groove diameter decreases stress slightly and reducing the width of the land at constant groove diameter also yields a minor reduction of peak stress.

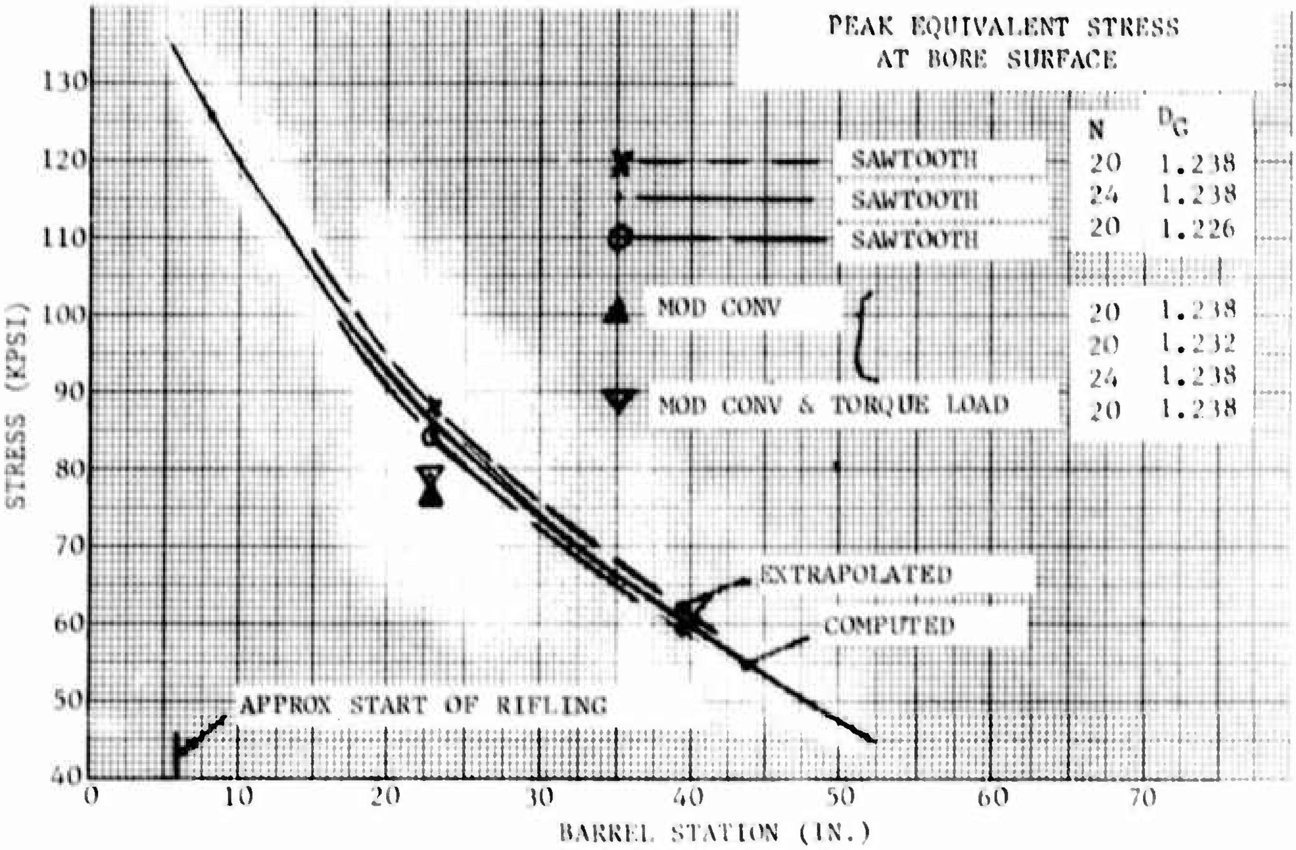
- The mod conventional configuration exhibits somewhat lower bore stress levels because of the reduced stress concentration at the groove crest.

2.3.4 RECOMMENDED RIFLING PROFILES

This study resulted in definition of rifling and rifling twist configurations for the test barrels shown in Table 4. The specific land and groove contours are illustrated in Figure 6.

TABLE 3. BARREL STRESS ANALYSIS CASES

Case No.	Rifling Type	Barrel Station (In.)	Number Lands	Groove Diameter (In.)	Land Width (In.)	Loading	σ_{eq} Max. Bore	σ_{eq} at r = 0.742 In.
1	Sawtooth	8.0	24	1.238	0.035	Pressure Only	126,250	
2		23.0	24	1.238	0.035		85,990	47,450
3		51.5	24	1.238	0.035		45,600	
4	Sawtooth	23.0	20	1.226	0.040	Pressure Only	34,400	46,350
5			20	1.238	0.040		87,850	48,050
6	Mod Conventional	23.0	24	1.238	0.042	Pressure Only	76,200	48,000
7			20	1.238	0.050		76,650	48,300
8			20	1.232	0.050		76,950	47,500
9	Mod Conventional	23.0	20	1.238	0.050	Pressure Plus Torque (Compare with Case 7)	79,200	48,700



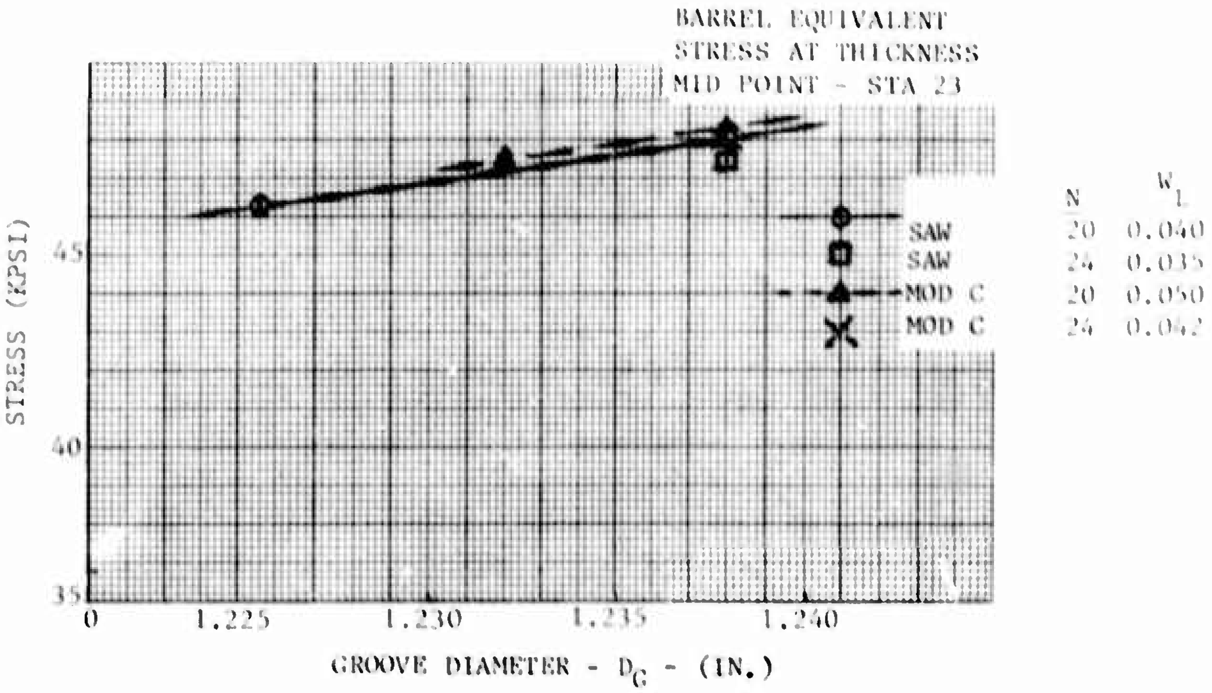


Figure 30. Barrel Stress Trends

TABLE 4. RIFLING PROFILES

	Sawtooth	Mod-Conventional	Existing GAU-8
Number of Grooves	24	24	20
Groove Diameter	1.234	1.232	1.226
Mean Bore Diameter	1.210	1.212	1.208
Land Width	0.043	0.053	0.080

SECTION III

BARREL FABRICATION

3.1 BARREL MATERIAL

Standard GAU-8 production barrel blanks (forged, heat treated, gun drilled, and rough machined) were purchased from Maremont Corp. The intent was to produce four deliverable barrels such that only the rifling would differ from standard production, thereby providing the Air Force with an opportunity to subsequently obtain unbiased test data on rifling effects.

The barrel blanks and subsequent processing were in accordance with DWG 201F158, "Barrel, Gun, 30mm," General Electric, dated 10/31/73 and revised 6/29/76.

3.2 RIFLING

The barrel blanks were rifled at Aeronutronic utilizing a technique of broaching two grooves simultaneously. A sine bar and rifling cutters were fabricated to produce the twist and groove shapes specified in Figures 5 and 6. Two barrels of each configuration were rifled. No difficulty was encountered in rifling either groove shape.

3.3 MACHINING AND FINISHING

The rifled barrel blanks were shipped to Maremont for chambering, chrome plating and finish machining. The barrels were phosphate coated and proof test fired in accordance with the aforementioned GAU-8 drawing. The approach was to dovetail these barrels into a GAU-8 barrel production run to assure that no process variations occurred. Finally the barrels were proof test fired and shipped to Aeronutronic where a spot check of critical dimensions was performed. In addition, full-length RTV silicone rubber replicas were made to provide a permanent record of bore dimensions. The four barrels (Figure 31) were shipped to Eglin AFB in March, 1976.

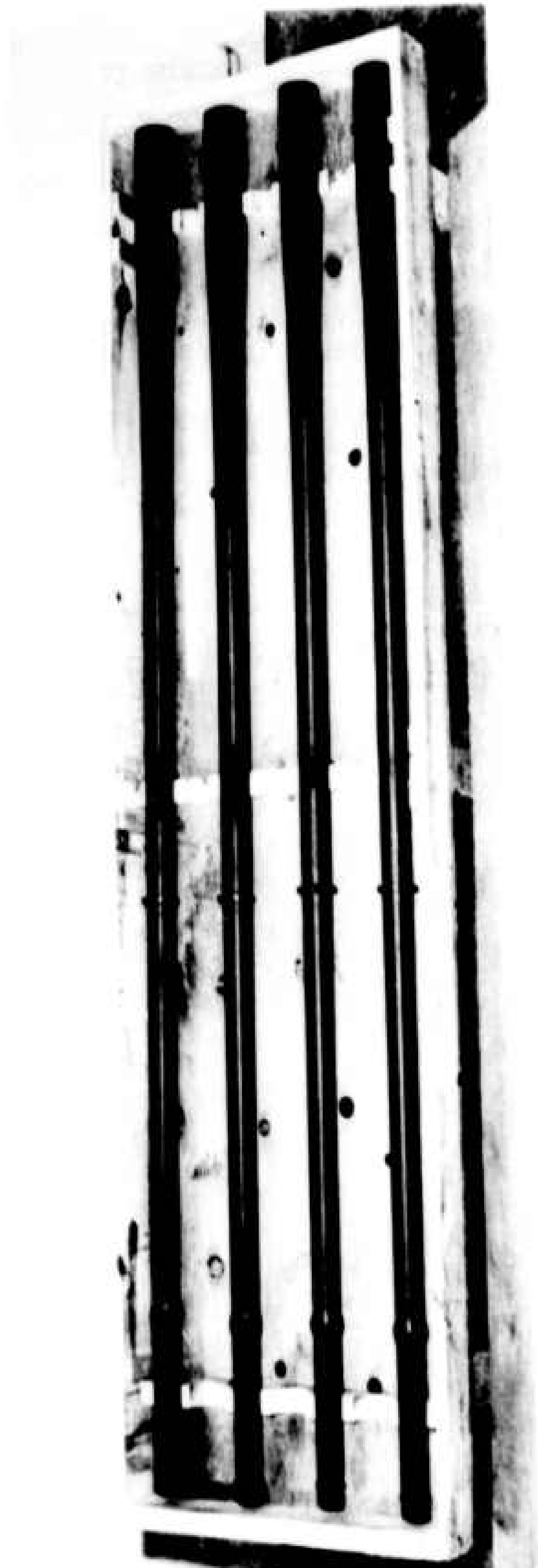


Figure 31. GAU-8 Gun Barrels Delivered to Eglin AFB

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Based on the design, analysis, and fabrication efforts described above, the following conclusions and recommendations were drawn:

(1) Rotating band stress can be significantly reduced by gain twist rifling as compared to constant twist.

(2) Increasing the number of lands and grooves reduces the rotating band stress. Minor variations in configuration of a given design (with the exception of sharp root fillets) have negligible impact on computed stress levels.

(3) Sawtooth and modified conventional rifling configurations can be successfully broached with no apparent differences in cost or resulting quality.

(4) The validity of the design and analysis efforts expended on this contract can best be proven by identically test firing the deliverable barrels and production GAU-8 barrels in a multishot mode.

APPENDIX A

GAU-8 BALLISTIC DATA

SHOT WEIGHT(LB)	CHARGE WEIGHT(LB)	WEB(INCHES)	BARREL LENGTH(INCHES)	CHAMBER VOLUME(CUBIC INCHES)	BORE AREA(SQUARE INCHES)
0.94300	0.32500	0.0320	84.0	18.420	1.100

MOLECULAR WEIGHT = 24.0 HEAT LOSS FACTOR IS 0.20 PROPELLANT USED IN SYSTEM IS HERC

PROPELLANT FORM IS SINGLE PERFORATE OR CONSTANT SURFACE

TIME	CHAMBER PRESSURE	TRAVEL	PROPELLANT BURNED	PRESSURE SLOPE	VELOCITY	BASE PRESSURE	TFLAME
0.00002	500.0	0.000	0.0003	3400645.5	0.00	500.0	2556.
0.00005	505.0	0.000	0.0007	3990039.4	0.00	505.0	2565.
0.00007	585.0	0.000	0.0011	4572933.1	0.00	605.0	2565.
0.00010	681.4	0.000	0.0016	5355300.4	0.00	681.4	2572.
0.00012	935.7	0.000	0.0022	6120912.9	0.00	935.7	2576.
0.00015	1000.7	0.000	0.0028	6914570.9	0.00	1000.7	2590.
0.00017	1251.5	0.000	0.0035	7745963.5	0.00	1251.5	2602.
0.00020	1455.3	0.000	0.0043	8670509.0	0.00	1455.3	2609.
0.00022	1672.2	0.000	0.0052	9842019.2	0.00	1672.2	2612.
0.00025	1910.3	0.000	0.0062	11200320.2	0.00	1910.3	2614.
0.00027	2190.3	0.000	0.0074	12543690.7	0.00	2190.3	2620.
0.00030	2511.9	0.000	0.0089	13905105.2	0.00	2511.9	2627.
0.00033	2851.0	0.000	0.0101	15702562.2	0.00	2851.0	2628.
0.00035	3255.0	0.000	0.0117	17577501.5	0.00	3255.5	2633.
0.00037	3695.2	0.000	0.0134	19422220.2	0.00	3695.2	2639.
0.00040	4100.5	0.000	0.0154	21400107.0	0.00	4102.9	2644.
0.00042	4718.0	0.000	0.0175	23002654.0	0.00	4710.0	2645.
0.00045	5314.5	0.000	0.0199	25000754.5	0.00	5314.5	2647.
0.00047	5979.8	0.000	0.0225	27709352.0	0.00	5979.9	2645.
0.00050	6724.5	0.000	0.0255	32992533.0	0.00	6724.5	2647.
0.00052	7549.3	0.000	0.0288	35543291.0	0.00	7549.3	2647.
0.00055	8452.0	0.001	0.0324	40510792.0	7.93	8402.5	2648.
0.00057	9475.5	0.005	0.0365	44770079.2	15.99	9475.5	2645.
0.00060	10595.1	0.011	0.0409	48792000.0	25.73	10595.0	2647.
0.00063	11814.9	0.021	0.0455	52459321.0	37.08	11814.7	2650.
0.00065	13120.1	0.034	0.0500	55245441.0	50.10	13125.7	2652.
0.00067	14532.2	0.051	0.0563	62145667.2	63.72	14531.4	2652.
0.00070	16035.6	0.073	0.0623	64111239.0	79.75	15934.4	2651.
0.00072	17530.7	0.099	0.0688	68252122.2	95.25	17635.2	2649.
0.00075	19341.0	0.130	0.0759	72027130.0	113.40	19337.1	2646.
0.00077	21141.7	0.167	0.0834	75249225.0	133.22	21135.5	2640.
0.00080	23047.9	0.210	0.0915	80569555.2	154.92	23238.7	2633.
0.00082	25052.1	0.259	0.1004	84574445.0	178.38	25040.7	2624.
0.00085	27170.0	0.316	0.1099	89457204.0	203.77	27159.7	2615.
0.00087	29392.4	0.383	0.1202	91756284.2	231.30	29303.1	2605.
0.00090	31695.3	0.457	0.1311	93009350.2	260.90	31647.5	2595.
0.00093	34012.5	0.540	0.1426	93001754.2	292.02	33961.1	2587.
0.00095	36339.3	0.633	0.1545	92099050.0	325.53	36259.0	2570.
0.00097	38541.0	0.736	0.1673	92140222.0	362.39	38540.0	2560.
0.00100	40406.5	0.851	0.1804	85721452.0	401.00	40775.4	2555.
0.00103	43253.5	0.977	0.1942	81533978.0	441.45	42929.1	2543.

0.00105	45104.4	1.116	0.2000	75012476.0	403.37	44000.0	2520.
0.00107	46994.7	1.268	0.2224	60757370.0	527.41	49750.1	2515.
0.00110	48713.8	1.433	0.2371	41204036.0	572.01	40410.0	2500.
0.00112	50243.7	1.512	0.2522	53112115.0	619.50	40077.2	2483.
0.00115	51571.5	1.805	0.2675	44550447.0	667.53	51131.7	2460.
0.00117	52600.0	2.012	0.2831	38029453.0	716.45	52105.0	2440.
0.00120	53500.7	2.235	0.2988	27410024.5	766.13	52870.7	2429.
0.00122	54274.8	2.472	0.3147	18974045.0	816.30	53500.2	2410.
0.00125	54740.3	2.724	0.3308	10076062.7	866.93	53940.0	2391.
0.00127	55028.3	2.992	0.3466	3247066.5	917.60	54100.1	2371.
0.00130	55101.5	3.275	0.3627	-3810049.6	960.37	54076.0	2351.
0.00132	55000.2	3.573	0.3787	-10224600.5	1010.07	53000.7	2331.
0.00135	54750.6	3.886	0.3947	-15951059.0	1060.03	53400.0	2311.
0.00137	54351.8	4.214	0.4105	-20973969.2	1110.78	52985.7	2291.
0.00140	53827.4	4.557	0.4263	-25200606.0	1167.77	52340.0	2271.
0.00142	53195.1	4.915	0.4420	-28039565.5	1219.15	51604.3	2252.
0.00145	52471.6	5.287	0.4575	-31043057.0	1263.74	50772.4	2232.
0.00147	51673.0	5.673	0.4728	-34354557.2	1318.40	49850.0	2214.
0.00150	50814.1	6.073	0.4880	-36224053.0	1350.31	48889.5	2195.
0.00152	49900.5	6.487	0.5030	-37612612.2	1401.21	47887.0	2176.
0.00155	48944.0	6.914	0.5177	-38509203.0	1445.15	46879.0	2160.
0.00158	48684.0	7.354	0.5323	-39155827.0	1486.27	45925.5	2143.
0.00160	47825.1	7.806	0.5467	-39420356.0	1530.81	44787.2	2127.
0.00162	46839.6	8.272	0.5608	-39412215.2	1572.06	43786.6	2112.
0.00165	45854.3	8.748	0.5748	-39175087.0	1613.91	42651.4	2096.
0.00167	44874.5	9.238	0.5887	-38751567.2	1649.00	41687.3	2082.
0.00170	43100.1	9.739	0.6023	-38174000.0	1687.09	40570.2	2068.
0.00172	42151.7	10.251	0.6157	-37475425.0	1724.64	39520.5	2054.
0.00175	41214.0	10.773	0.6289	-36600759.0	1761.09	38502.3	2041.
0.00177	40297.0	11.307	0.6420	-35813441.0	1796.20	37613.4	2028.
0.00180	39402.5	11.851	0.6548	-34902789.2	1830.02	36802.2	2017.
0.00182	38527.7	12.405	0.6674	-34169453.0	1854.12	35769.5	2005.
0.00185	37673.4	12.969	0.6798	-33309479.5	1899.74	34807.5	1995.
0.00187	36840.0	13.543	0.6920	-32413017.5	1920.57	34019.7	1984.
0.00190	36030.4	14.126	0.7039	-31585333.5	1950.01	33191.5	1974.
0.00192	35242.0	14.719	0.7157	-30509259.2	1986.00	32378.3	1965.
0.00195	34470.1	15.320	0.7273	-29872507.5	2019.44	31504.5	1955.
0.00197	33736.3	15.930	0.7387	-28760157.0	2040.25	30825.1	1945.
0.00200	33017.3	16.549	0.7499	-27930112.5	2075.47	30092.7	1938.
0.00202	32320.0	17.176	0.7610	-26071015.5	2103.00	29301.2	1932.
0.00205	31640.5	17.811	0.7719	-25121905.5	2130.90	28609.0	1922.
0.00207	30994.2	18.454	0.7826	-25253373.5	2155.00	28034.5	1914.
0.00210	30362.7	19.105	0.7931	-24420932.5	2182.49	27309.0	1907.
0.00212	29752.0	19.764	0.8035	-23569131.5	2207.50	26779.5	1900.
0.00215	29150.3	20.430	0.8137	-22002032.5	2231.00	26184.3	1893.
0.00217	28585.4	21.123	0.8237	-22329425.5	2255.07	25587.3	1885.
0.00220	28027.0	21.783	0.8335	-21002013.0	2279.20	25046.5	1880.
0.00223	27485.2	22.470	0.8432	-21247761.2	2302.13	24587.3	1874.
0.00225	26958.0	23.154	0.8527	-20430999.2	2324.52	23983.2	1868.
0.00227	26440.2	23.865	0.8620	-19930900.5	2346.42	23475.7	1862.
0.00230	25952.4	24.578	0.8711	-19249059.5	2367.07	22906.4	1857.
0.00233	25471.2	25.285	0.8801	-18502354.5	2388.05	22500.6	1851.
0.00235	25004.2	26.005	0.8889	-18133009.0	2409.42	22047.0	1846.
0.00237	24552.0	26.731	0.8976	-17022574.5	2429.50	21601.9	1841.
0.00240	24110.0	27.463	0.9061	-17000234.5	2449.29	21190.5	1835.
0.00242	23683.6	28.20	0.9145	-16502022.0	2468.63	20750.9	1831.
0.00245	23260.4	28.94	0.9228	-16109431.5	2487.50	20345.4	1827.
0.00247	22866.1	29.693	0.9309	-15944319.2	2506.17	19952.5	1822.
0.00250	22474.6	30.440	0.9389	-15195195.7	2524.48	19571.7	1818.

0.00252	22095.1	31.288	0.9468	-14781980.5	2542.28	19282.0	1813.
0.00255	21726.2	31.973	0.9545	-14343378.2	2559.82	18844.0	1808.
0.00257	21367.4	32.744	0.9623	-13939173.0	2577.03	18407.0	1806.
0.00260	21019.8	33.519	0.9697	-13540871.0	2593.93	18101.3	1801.
0.00262	20680.2	34.300	0.9771	-13172020.2	2610.51	17834.0	1797.
0.00265	20350.5	35.088	0.9844	-12828178.5	2626.88	17510.8	1793.
0.00267	20030.7	35.878	0.9916	-12459983.7	2642.90	17210.5	1790.
0.00270	19719.3	36.671	0.9987	-12189141.0	2658.52	16812.1	1788.
0.00272	19416.7	37.471	1.0057	-11769991.2	2673.90	16622.5	1785.
0.00275	19122.5	38.276	1.0057	-20245387.5	2689.14	16341.5	1793.
0.00278	18816.3	39.085	1.0057	-19407444.5	2703.09	15901.8	1781.
0.00280	18131.2	39.898	1.0057	-18814349.5	2718.22	15448.5	1771.
0.00282	17645.0	40.715	1.0057	-17803217.5	2732.15	15019.0	1760.
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0.00288	16780.4	42.363	1.0057	-16478862.7	2758.90	14088.0	1738.
0.00290	16378.5	43.192	1.0057	-15839314.2	2771.73	13857.7	1729.
0.00292	15982.1	44.026	1.0057	-15220590.5	2784.24	13502.0	1720.
0.00295	15981.9	44.863	1.0057	-14851437.7	2796.42	13100.9	1718.
0.00297	15235.6	45.704	1.0057	-14102692.7	2808.33	12832.0	1701.
0.00300	14883.2	46.548	1.0057	-13581549.7	2819.97	12517.6	1692.
0.00302	14543.5	47.396	1.0057	-13005511.3	2831.17	12216.1	1683.
0.00305	14215.4	48.247	1.0057	-12813387.7	2842.10	11923.6	1674.
0.00307	13921.2	49.101	1.0057	-12163787.0	2852.64	11643.0	1666.
0.00310	13596.9	49.958	1.0057	-11735411.2	2863.44	11374.8	1657.
0.00312	13383.5	50.818	1.0057	-11327044.5	2873.09	11114.2	1649.
0.00315	13228.4	51.682	1.0057	-10937555.2	2883.71	10863.3	1641.
0.00317	12749.9	52.549	1.0057	-10595000.2	2893.90	10622.5	1633.
0.00320	12482.9	53.419	1.0057	-12211029.5	2903.07	10389.7	1626.
0.00322	12227.5	54.291	1.0057	-9872874.5	2912.43	10165.1	1618.
0.00325	11980.7	55.166	1.0057	-9540145.2	2921.59	9948.3	1611.
0.00327	11742.0	56.044	1.0057	-9238427.5	2930.55	9738.0	1603.
0.00330	11511.2	56.924	1.0057	-8942158.8	2939.32	9536.0	1596.
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0.00335	11071.0	58.693	1.0057	-8387149.7	2956.32	9151.9	1582.
0.00337	10851.3	59.581	1.0057	-8127103.2	2964.53	8969.0	1578.
0.00340	10658.2	60.472	1.0057	-7877899.5	2972.58	8792.1	1569.
0.00342	10451.2	61.365	1.0057	-7639076.4	2980.50	8620.7	1563.
0.00345	10272.2	62.262	1.0057	-7400015.2	2988.25	8454.0	1558.
0.00347	10055.0	63.159	1.0057	-7189022.1	2995.84	8294.1	1550.
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0.00355	9551.4	65.864	1.0057	-6581286.5	3017.75	7840.8	1532.
0.00357	9366.8	66.770	1.0057	-6394256.5	3024.80	7699.0	1529.
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0.00362	9081.4	68.590	1.0057	-6042009.7	3038.48	7427.1	1519.
0.00365	8932.6	69.502	1.0057	-5874281.2	3045.13	7297.1	1520.
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0.00370	8640.5	71.333	1.0057	-5559403.0	3058.08	7049.3	1498.
0.00372	8501.5	72.251	1.0057	-5410729.0	3064.30	6929.1	1493.
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0.00377	8235.0	74.093	1.0057	-5129212.0	3076.59	6700.5	1483.
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0.00382	7991.9	75.943	1.0057	-4867440.1	3088.55	6484.2	1473.
0.00385	7880.2	76.870	1.0057	-4743431.1	3094.34	6382.4	1458.
0.00387	7741.5	77.800	1.0057	-4623723.9	3100.03	6279.3	1463.
0.00390	7626.0	78.730	1.0057	-4508140.1	3105.63	6180.2	1458.
0.00392	7513.3	79.663	1.0057	-4396501.7	3111.14	6085.0	1453.
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0.00397	7296.2	81.533	1.0057	-4184397.0	3121.89	5900.5	1444.

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